



Seismic Performance Assessment of Buildings

Volume 2 – Implementation Guide
Second Edition

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Second Edition

Prepared by

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Cover photograph – Collapsed building viewed through the archway of an adjacent building, 1999 Chi-Chi, Taiwan earthquake (courtesy of Farzad Naeim, Farzad Naeim, Inc).

Preface

In 2001, the Applied Technology Council (ATC) was awarded the first in a series of contracts with the Federal Emergency Management Agency (FEMA) to develop Next-Generation Performance-Based Seismic Design Guidelines for New and Existing Buildings. These projects would become known as the ATC-58 series of projects. The overall program was separated into two major phases of work: Phase 1 – Developing a Methodology for Assessing the Seismic Performance of Buildings; and Phase 2 – Developing Performance-Based Seismic Design Procedures and Guidelines.

This report is one of three principal products of the Phase 1 work, which were first published in 2012, and have since been updated under the Phase 2 work:

- FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology, Second Edition*
- FEMA P-58-2, *Seismic Performance Assessment of Buildings, Volume 2 – Implementation Guide, Second Edition*
- FEMA P-58-3, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation, Third Edition*

The three volumes together describe the seismic performance assessment methodology for individual buildings, as well as the development of basic building information, response quantities, fragilities, and consequence data used as inputs to the methodology. The procedures are probabilistic, uncertainties are explicitly considered, and performance is expressed as the probable consequences, in terms of human losses (deaths and serious injuries), direct economic losses (building repair or replacement costs), and indirect losses (repair time, unsafe placarding, and environmental impacts) resulting from building damage due to earthquake shaking.

The purpose of this *Volume 2 –Implementation Guide, Second Edition* is to provide users with step-by-step guidance in the development of basic building information, response quantities, fragilities, and consequence data used as inputs to the methodology.

To allow for practical implementation of the methodology, work included the collection of fragility and consequence data for most common structural systems and building occupancies, and the development of an electronic *Performance Assessment Calculation Tool* (PACT) for performing the probabilistic computations and accumulation of losses, which were also updated as part of the Phase 2 work.

Updates include technical improvements to the methodology, and revisions to the underlying fragility and consequence data, to take advantage of the latest research, and to bring results into better alignment with expectations based on the performance of buildings in past earthquakes. Phase 2 also included the development of additional volumes intended to expand and complete FEMA P-58 series of products to communicate seismic performance to stakeholders, quantify the seismic performance capability of typical code-conforming buildings, and provide performance-based design guidance to assist decision-makers in choosing between seismic design criteria and making seismic design decisions.

The FEMA P-58 series of products is the result of the collaborative effort of more than 200 individuals, across all phases, involved in the development of the methodology and subsequent products and reports. Phase 1 consultants were involved in the development of the basic assessment methodology, collection of available fragility data, estimation of consequences, development of supporting electronic tools, implementation of quality assurance procedures, and beta testing efforts. ATC is indebted to the Phase 1 leadership of Ron Hamburger, who served as Project Technical Director, Bob Bachman, who served as Nonstructural Performance Products Team Leader, John Hooper and Craig Comartin, who served as Risk Management Products Team Leaders, Andrew Whittaker, who served as Structural Performance Products Team Leader, and the members of the Phase 1 Project Management Committee, including John Gillengerten, Bill Holmes, Peter May, Jack Moehle, and Maryann Phipps. ATC is also indebted to Andy Merovich, Structural Performance Products Team Member, for his lead role in the development of the First Edition of this volume.

Phase 2 consultants were responsible for the update of all Phase 1 products, and the development of new performance-based design guidance and stakeholder guidance. ATC is indebted to the Phase 2 leadership of Ron Hamburger, who continued to serve as the Project Technical Director, John Gillengerten, who served as Performance Products Team Leader, John Hooper, who served as Products Update Team Leader, Laura Samant, who served as Stakeholder Products Team Leader, and the members of the

Phase 2 Project Management Committee, including Bill Holmes, Steve Mahin, Jack Moehle, Khalid Mosalam, and Steve Winkel.

ATC would also like to thank the members of the Phase 1 and Phase 2 Project Steering Committees, the Fragility Review Panel, the Nonstructural Performance Products Team, the Performance Products Team, the Products Update Team, the Risk Management Products Team, the Stakeholder Products team, the Structural Performance Products Team, the Validation/Verification Team, and the many consultants who assisted these teams. The names of individuals who served in these groups, along with their affiliations, are provided in the list of Project Participants at the end of this report.

ATC acknowledges the Pacific Earthquake Engineering Research Center (PEER), and its framework for performance-based earthquake engineering, as the technical basis underlying the methodology. In particular, the work of Tony Yang, Jack Moehle, Craig Comartin, and Armen Der Kiureghian in developing and presenting the first practical application of the PEER framework, is recognized as the basis for how computations are performed and losses are accumulated in the methodology.

Special acknowledgment is extended to C. Allin Cornell and Helmut Krawinkler for their formative work in contributing to risk assessment and performance-based design methodologies, and to whom this work is dedicated.

ATC also gratefully acknowledges Michael Mahoney (FEMA Project Officer) and Robert Hanson (FEMA Technical Monitor) for their input and guidance in the conduct of this work, and Bernadette Hadnagy, Peter N. Mork, and Carrie Perna for ATC report production services.

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This *Second Edition Implementation Guide* provides guidance on implementation and use of the methodology set forth in FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology, Second Edition*, (FEMA, 2018a) to assess the seismic performance of individual buildings based on their unique site, structural, nonstructural, and occupancy characteristics, expressed in terms of the probability of incurring casualties, repair and replacement costs, repair time, environmental impacts, and unsafe placarding. This *Implementation Guide* contains examples illustrating the performance assessment process, including selected calculation and data generation procedures, as well user manuals for selected electronic tools provided in FEMA P-58-3, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation*, (FEMA, 2018b).

This *Implementation Guide*, and its companion Volumes 1 and 3, were first published in 2012. Shortly after publication, a second phase of work was initiated to update and complete the FEMA P-58 series of products, including exercising the methodology to assess the performance of code-conforming buildings, developing products for communicating seismic performance to stakeholders, and developing design guidance to assist decision-makers in choosing between seismic design criteria and making seismic design decisions. Technical improvements and updates to the methodology were developed, as necessary, to take advantage of the latest research and to bring assessment results into better alignment with expectations based on performance observed in past earthquakes.

1.1 Purpose and Scope

The general methodology presented in Volume 1 can be applied to seismic performance assessments of any building type, regardless of age, construction or occupancy type. Many different means of implementing this general methodology are possible. During the development of the general methodology, the project development team found it necessary to develop a tool to implement the methodology, which is provided in Volume 3 as the *Performance Assessment Calculation Tool* (PACT). The problem

Second Edition Update
Significant updates in the Second Edition are identified with green margin boxes throughout the document.

Second Edition Update
All chapters have been updated to present screenshots from PACT version 3.1.2.

formulation and execution process outlined in this *Implementation Guide* is sequenced to correspond to the input cues provided by PACT.

This *Implementation Guide* provides a detailed road map for users to follow in applying the FEMA P-58 methodology to the site, structural, nonstructural, and occupancy characteristics of their individual building to obtain intensity-based, scenario-based, or time-based earthquake performance assessments. Implementation requires basic data on the vulnerability of structural and nonstructural components to damage (fragility), as well as estimates of potential casualties, repair costs, repair times, and environmental impacts (consequences) associated with this damage. This document also provides examples for calculating user-defined structural and nonstructural fragilities, and developing consequence functions.

1.2 Limitations

This document tracks with the provisions of Volume 1, but does not substantially duplicate its narratives, definitions, equations, or other provisions. Readers are cautioned to use this document in conjunction with Volume 1, and not to rely on Volume 2 alone for guidance on executing the methodology.

1.3 The Performance Assessment Process

Figure 1-1 illustrates the basic steps in the performance assessment process. Volume 1 describes each of these steps and how they relate to the overall performance assessment. Three of these steps, assembling building performance model, defining earthquake hazards, and analyzing building response, in addition to developing collapse fragility, when necessary, are performed directly by the user. This *Implementation Guide* presents illustrations of these steps with examples ranging from simple to more complex.

Before implementing the assessment process, however, the user should select the assessment type, analysis method, and performance measures that will provide the desired output.

1.3.1 Assessment Types

Volume 1 defines three different seismic performance assessment types. Each assessment type requires different input and utilizes different procedures.

Intensity-based assessments evaluate a building's probable performance assuming that it is subjected to a specified earthquake shaking intensity. Shaking intensity is defined by 5% damped, elastic acceleration response spectra. This type of assessment can be used to assess a building's performance in the event of design earthquake shaking consistent with a building code response spectrum, or to assess performance for shaking intensity represented by any other response spectrum.

Scenario-based assessments evaluate a building's probable performance assuming that it is subjected to a specified earthquake scenario consisting of a specific magnitude earthquake occurring at a specific location relative to the building site. Scenario assessments may be useful for buildings located close to one or more known active faults. This type of assessment can be used to assess a building's performance in the event of a historic earthquake on these faults is repeated, or a future projected earthquake occurs.

Time-based assessments evaluate a building's probable performance over a specified period of time (e.g., 1-year, 30-years, or 50-years) considering all earthquakes that could occur in that time period, and the probability of occurrence associated with each earthquake. Time-based assessments consider uncertainty in the magnitude and location of future earthquakes as well as the intensity of motion resulting from these earthquakes.

1.3.2 Performance Measures

The seismic performance of a building is expressed as the probable damage and resulting consequences of a building's response to earthquake shaking. The consequences, or impacts, resulting from earthquake damage considered in this methodology are:

- **Casualties.** Loss of life or serious injury requiring hospitalization, occurring within the building envelope.
- **Repair cost.** The cost, in present dollars, necessary to restore a building to its pre-earthquake condition, or in the case of total loss, to replace the building with a new structure of similar construction.
- **Repair time.** The time necessary to repair a damaged building to its pre-earthquake condition. The repair time estimates do not include the time needed to design, permit, and fund the repair project, the time to procure long lead time components that require replacement, or the time to mobilize the contractors and finalize the project.
- **Unsafe placarding.** A post-earthquake inspection rating that deems a building or portion of a building damaged to the point that entry, use, or occupancy poses immediate risk to safety.

Second Edition Update

Consideration of environmental impacts is included in accordance with the updated *Methodology*.

- **Environmental Impacts.** Environmental impacts, in terms of carbon emissions and embodied energy, to restore a building to its pre-earthquake condition, or in the case of total loss, to replace the building with a new structure of similar construction.

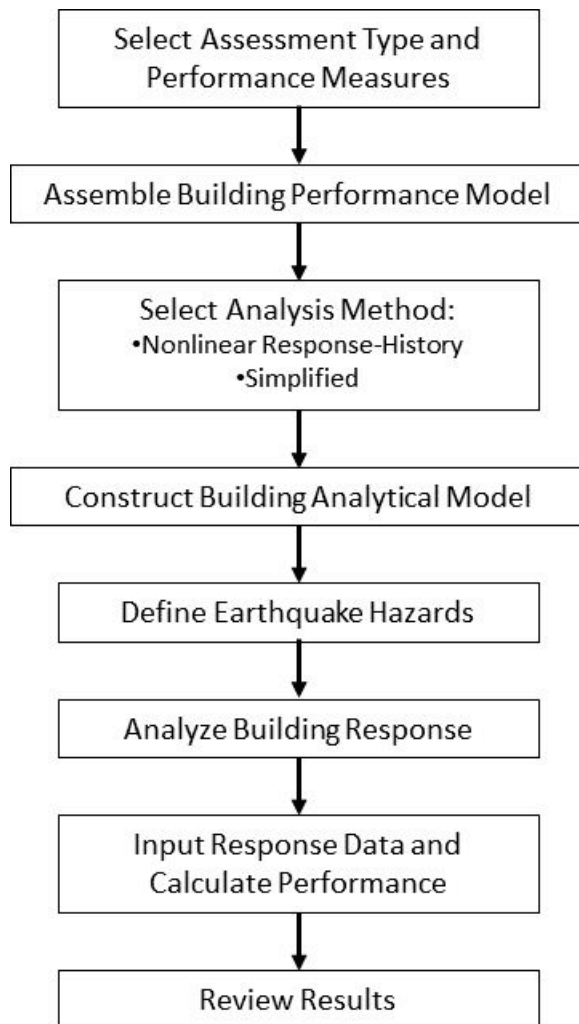


Figure 1-1 Performance assessment process.

Each performance measure requires basic information about the building's characteristics.

1.3.3 Analysis Methods

The methodology provides users with a range of options for generating the above assessments. Options include use of a simplified analytical estimation of building response or suites of detailed nonlinear response history analyses. Building assets at risk can be defined by occupancy-dependent typical (normative) quantities or building-specific surveys. The performance characteristics of these at-risk assets can be represented by provided

relationships for component fragility and consequences, or component-specific fragility and consequence functions can be developed and used. Each building performance assessment can use either of the analysis approaches or any combination of the options to define component fragility and consequence characteristics.

The simplest application of the methodology includes use of the simplified analysis method to estimate building response and the selection of provided, occupancy-dependent fragility and consequence functions for the building assets at risk. This streamlined approach may be most appropriate for circumstances where information about building characteristics is limited, as is typical during preliminary design of new buildings or in the initial evaluation stages for existing buildings. In general, the more streamlined the approach, the more limitations there are in the methodology's ability to characterize performance and the larger the inherent uncertainty in the performance assessments.

1.4 Updates to Implementation Tools

Originally developed in 2012, this *Implementation Guide* provided example applications of the FEMA P-58 methodology and tools, using various online and external resources available at the time. Phase 2 updates to the fragility database include new fragility and consequence data, and editorial changes to fragilities such as revised numbering and addition or deletion of selected fragilities. Changes to fragility and consequence information are documented in FEMA P-58/BD-3.7.19 (FEMA, 2018e). Because of changes to the fragility database, a building model developed using a previous version of PACT may cause an error. This *Second Edition Implementation Guide* reflects updates that have been made to the FEMA P-58 methodology, tools, and underlying data. References to online tools and outside resources have been updated; however, the ongoing availability of resources developed external to the project (e.g., online tools for constructing hazard curves) is subject to change, and current versions may not be comprehensively covered herein. Other resources may also become available.

Second Edition Update

Most tools provided as part of the FEMA P-58 series of products have been updated since the original publication in 2012.

Volume 3 – Supporting Electronic Materials and Background

Documentation, Third Edition includes the following electronic products to assist in the implementation and use of the methodology:

- *Performance Assessment Calculation Tool (PACT)*. PACT is an electronic calculation tool, and repository of fragility and consequence data, that performs the probabilistic calculations and accumulation of losses described in the methodology. It includes a series of utilities used to specify building properties and update or modify fragility and

consequence information in the referenced databases. An executable file (.exe) is provided to facilitate installation of the tool. Appendix C of this Volume presents a User Manual for PACT.

- *Provided Fragility Data.* This folder contains the following products to aid management, maintenance of all provided fragility and consequence data outside of PACT and assist in the development of consequences for custom fragility specifications:
 - *Fragility Database* is an Excel workbook that is used to review and maintain all provided fragility and consequence data outside of PACT. This database has been updated for the Second Edition release and includes environmental impact consequence information.
 - *Fragility Specification* is a PDF file displaying the contents of the fragility database. Each fragility specification contains fragility and consequence data for the component of interest, in a one-page format. Damage states are illustrated with photos of representative damage, when available.
 - *PACT Input Matrix* is an Excel workbook that contains the Fragility Database in a format that is required for upload into PACT.
 - *Consequence Estimation Summary* is an Excel workbook that provides the basis for provided consequence data, and can be used to assist in estimating consequences for custom fragility specifications.
- *Normative Quantity Estimation Tool* is an Excel workbook designed to assist in estimating the type and quantity of nonstructural components typically present in buildings of a given occupancy and size. Appendix D of this Volume presents a User Manual for this tool.
- *Performance Estimation Tool (PET).* PET is an Excel workbook that utilizes assessment results from the application of the FEMA P-58 methodology to a group of archetypical building representative of structures conforming to the seismic design requirements of the current building code. The tool can be used as a design aid to obtain an initial estimate of required design strength and drift ratio necessary to achieve a desired performance objective.
- *Static Pushover to Incremental Dynamic Analysis (SPO2IDA).* SPO2IDA is an Excel workbook application that was originally developed by Vamvatsikos and Cornell (2006). This tool uses empirical relationships from a large database of incremental dynamic analysis results to convert static pushover curves into probability distributions for building collapse as function of ground shaking intensity.

Second Edition Update

This is a newly developed tool and is described in FEMA P-58, Volume 5 and FEMA P-58, Volume 6.

- *Collapse Fragility Tool*. The Collapse Fragility Tool is an Excel workbook application that fits a lognormal distribution to collapse statistics obtained from a series of nonlinear dynamic analyses at different ground motion intensity levels.

With the exception of the *Performance Estimation Tool* (PET), this *Implementation Guide* illustrates the use of all tools listed above. Use of the *Performance Estimation Tool* for viewing assessment results is described in FEMA P-58-5, *Guidelines for Performance-Based Seismic Design of Buildings* (FEMA, 2018c), and use of the tool as a design aid is presented in FEMA P-58-6, *Guidelines for Performance-Based Seismic Design of Buildings* (FEMA, 2018d).

1.5 Organization and Content

This *Implementation Guide* is organized into the following chapters:

Chapter 2 provides a detailed description of the steps used to develop a building performance model consisting of basic building information, structural and nonstructural fragility specifications, consequence functions, and the building's collapse fragility and residual drift characteristics.

Chapter 3 provides a detailed description of the steps required to execute intensity, scenario, and time-based assessments.

Chapter 4 provides a step-by-step application of the methodology for an intensity-based assessment that uses simplified analysis for estimating building response and relies on provided fragility and consequence functions to characterize component vulnerability.

Chapter 5 provides a step-by-step application of the methodology for a time-based assessment that uses nonlinear response history analyses for estimating building response.

Chapter 6 illustrates development of structural component fragility functions by calculation to address unique circumstances or to supplement the provided fragility functions.

Chapter 7 illustrates development of nonstructural component fragility functions by calculation to address unique circumstances or to supplement the provided fragility functions.

Chapter 8 provides guidance on the development of component consequence functions to accompany user-defined fragility functions and to supplement or modify provided consequence functions.

Appendix A lists structural components for which fragility and consequence data are provided.

Appendix B lists nonstructural components and contents for which fragility and consequence data are provided.

Appendix C provides instructions for the use of PACT.

Appendix D describes the *Normative Quantity Estimation Tool* that is designed to assist in estimating the type and quantity of nonstructural components typically present in buildings of a given occupancy and size.

A Glossary and list of Symbols, providing definitions of key terminology and notation used in the methodology, along with a list of References, are provided at the end of this report.

Chapter 2

Building Performance Model

2.1 Introduction

This chapter provides guidance for assembling the building performance model and is organized to provide direct references to the appropriate input tabs the user will find in the *Performance Assessment Calculation Tool* (PACT) provided in Volume 3. Figure 2-1 illustrates the format of PACT screenshots provided throughout this document.

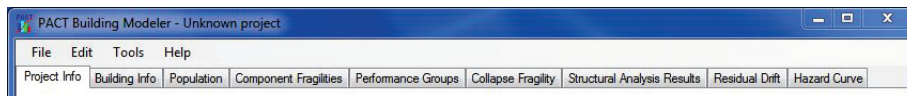


Figure 2-1 Format of PACT screenshots used, indicating the tab title location.

The building performance model provides a systematic and quantitative description of the building assets at risk of damage from earthquake ground shaking effects. This model includes basic building characteristics (Section 2.2), an overview of fragility specifications and performance groups (Section 2.3), an organized description of the structural (Section 2.4) and nonstructural (Section 2.5) components, the location of these assets within the building, an expression of their damageability and the consequences of this damage, as well as a collapse fragility function (Section 2.6) expressing the probability of building collapse, and a residual drift function (Section 2.7) which is a measure of the building's repairability.

2.2 Building Characteristics

2.2.1 Project Information

Assembly of the building performance model within PACT begins with the **Project Info** tab, shown in Figure 2-2. This is used to input basic project information used to identify the analysis files and results including **Project ID**, **Building Description**, **Client**, and **Engineer** fields.


PACT uses the **Region Cost Multiplier** and **Date Cost Multiplier** fields to adjust provided component repair cost consequence functions to appropriate present values. The provided consequence functions reflect repair costs appropriate to Northern California in 2011. Users can address escalation and regional cost variation through cost multiplier input using any suitable cost

index system. The cost modifier applies only to the cost data provided in the PACT consequence function database. If the user provides building-specific consequence cost data, these data should directly reflect the cost index associated with the building's locality and the assessment time, before insertion into the performance model. If the user inputs independently derived consequence functions for all of the performance groups included in the assessment, the region and date cost multipliers should be input as a value of 1.0.

Figure 2-2 PACT Project Information tab.

PACT uses the **Solver Random Seed Value** input to initiate all internally programmed sequences of random number generation utilized in performance assessment. If a **Solver Random Seed Value** of zero is used, PACT will randomly seed each generation sequence. This will result in different values for performance assessment results each time the same problem is executed even if there are no changes to the input. While the results of these assessments can be expected to be similar, users should input a single digit non-zero integer to avoid seeing anomalous changes in predicted performance when multiple evaluations of the same building are performed. Note that if a sufficiently large number of realizations is used, this effect is negligible.

2.2.2 Building Information

Figure 2-3 illustrates the **Building Info** tab used to enter basic building data. The red exclamation symbol, , appears whenever the value of an input is outside a reasonable range, indicating a probable input error. This occurs for many fields before data are entered, as a warning that entry is required.

PACT Building Modeler - Unknown project

File Edit Tools Help

Project Info Building Info Population Component Fragilities Performance Groups Collapse Fragility Structural Analysis Results Residual Drift Hazard Curve

Number of Stories: 1

Total Replacement Cost (\$): 0 Replacement Time (days): 24.00 Total Loss Threshold (As Ratio of Total Replacement Cost): 1

Core and Shell Replacement Cost (\$): 0 Max Workers per sq. ft.: 0.001

Carbon Emissions Replacement (kg): 0 Embodied Energy Replacement (MJ): 0

Most Typical Defaults

Floor Area (sq. ft.): 0.00 Story Height (ft.): 0

Floor Num	Floor Name	Story Height (ft.)	Area (ft.)	Height Factor	Hazmat Factor	Occupancy Factor
1	Floor 1	0.00	0.00	1	1	1
2	Floor 2	0.00	0.00	1	1	1

Figure 2-3 PACT Building Information tab.

PACT uses the **Number of Stories** input as a basic index of the number of demand parameters, performance groups, and calculations to be performed. A story is defined as the building volume that extends from the top of slab or other flooring at one floor level, to the top of slab or flooring at the next level. It includes all things that are mounted on or above the lower floor and which are present beneath the top of the higher level, such as the framing supporting the higher floor or roof. The input value should include all stories that have vulnerable components and which are to be included in the performance assessment. If basements are present, and have vulnerable structural or nonstructural components or occupants susceptible to injury, these should be included as stories. Similarly, penthouses with vulnerable components or occupants should be included as stories.

PACT defines the number of floors based on the **Number of Stories** input, where floor identifies all those components present within a story that are located on top of the surface of the identified floor, and beneath the top surface of the floor above. Thus, the first floor includes fragility groups for framing that supports (and is beneath) the second floor; as well as components that are supported on the first floor or suspended from the second floor.

Figure 2-4 illustrates the PACT definitions of floor and story numbers and floor and story heights. Floor numbering should be initialized at the lowest story housing damageable components. In the example of Figure 2-4, it has been assumed that basement stories of this building do not contain damageable components.

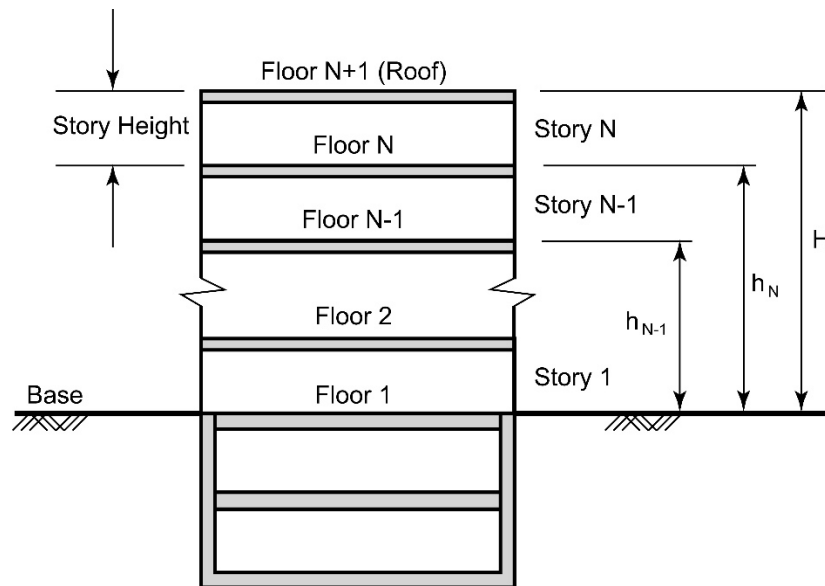


Figure 2-4 Definition of floor and story numbers and floor and story heights.

Core and Shell Replacement Cost should reflect a best estimate of the cost to replace all building core and shell items, including an allowance for building demolition and site clearance. Core and shell components include the basic building structure and cladding and all nonstructural components that are not typically provided by the tenants, such as elevators, stairs, toilet rooms, and basic electrical and mechanical service. **Total Replacement Cost** input includes the cost of core and shell constituents plus the cost to replace tenant improvements and contents. Tenant improvements commonly include office partitions, ceilings, light fixtures, HVAC, and electrical distribution within occupied spaces except in common areas, such as lobbies or central plants.

The **Maximum Workers per Square Foot** input is used to calculate repair time. Values for this parameter should range from 0.0005 (one worker per 2,000 square feet) to 0.004 (1 worker per 250 square feet). During an actual repair project there can be considerable fluctuation in the number of workers per square foot of floor area. PACT provides a default setting of 0.001 which corresponds to one worker per 1000 square feet of floor area. Users should generally execute their assessment with this default value, but can use denser values when the building occupancy is such that owners will be willing to bear the cost associated with more rapid repair schedules. Use of denser values will typically imply that the building will not be occupied during repair, even if damage is not so great as to warrant this from other perspectives. Users can perform multiple assessments using different values of this parameter to understand how it affects the potential repair times.

The **Total Loss Threshold** is the ratio of repair cost to replacement cost at which a decision will likely be made to replace the building rather than repair it. FEMA uses a value of 0.5 for this loss ratio when determining whether post-earthquake repair should be funded. PACT uses a default value of 1.0 to maximize the amount of assessment information that will be obtained in an assessment. Volume 1 suggests that when repair costs exceed 40% of replacement costs, many owners will choose to demolish the existing building and replace it with a new one.

The **Carbon Emissions Replacement** is the total carbon impact of replacing the building. This is calculated by multiplying the **Total Replacement Cost** by the appropriate construction sector impacts from the United States Environmentally Extended Input-Output (USEEIO) database (available at: <https://catalog.data.gov/dataset/useeio-v1-1-matrices>, last accessed September 28, 2018). For example, if the total replacement cost of the building is \$1,000,000 and the global warming potential (labeled in the dataset as “*impact potential/gcc/kg co2 eq*”) for the sector “2332a0/commercial structures, including farm structures/us” is 0.414 kg CO₂e per \$1 (reference year 2013), and the inflation factor from 2013 to 2011 is assumed to be 0.88 (based on the ratio of gross domestic product in the construction sector in 2013 to 2011 from U.S. Bureau of Economic Analysis, available at <https://www.bea.gov/>, last accessed September 28, 2018), the resulting carbon emissions impact of building replacement would be $(0.414 \text{ kg CO}_2\text{e}/\$) \times (\$1,000,000) / (0.88) = 470,454 \text{ kg CO}_2\text{e}$.

Second Edition Update
Environmental impact
considerations were added.

The **Embodied Energy Replacement** is the total embodied energy impact of replacing the building. This is calculated by multiplying the **Total Replacement Cost** by the appropriate construction sector impacts from the USEEIO dataset. For example, if the total replacement cost of the building is \$1,000,000 and the energy impact (labeled in the dataset as “*resource use/enrg/mj*”) for the sector “2332a0/commercial structures, including farm structures/us” is 5.729 MJ per \$1 (reference year 2013), and the deflation factor from 2013 to 2011 is assumed to be 0.88, the resulting carbon emissions impact of building replacement would be $(5.729 \text{ MJ}/\$) \times (\$1,000,000) / (0.88) = 6,510,227 \text{ MJ}$.

The information placed in the **Most Typical Default** section is used to populate a matrix of values for each floor, identified in the lower portion of the tab. Users can change the values in the matrix by entering other values directly into the individual cells. **Floor Area** input is used to estimate the number of casualties during an earthquake realization. **Story Height** is not used within PACT, but input of a reasonable value is required.

In this matrix, the **Height Factor** is used to reflect increases in repair cost attributable to:

- Loss of efficiency due to added travel time to get to damaged components on upper levels
- Material and tool loading and staging, including added cost for hoisting, elevator loading, pumping, and disposal
- Access costs related to cutting openings or penetrations, removing windows, loading and moving material to installation areas
- Scaffolding or rigging, including fall protection and protection to lower areas

Minor cost adjustments may be appropriate for simple interior repairs, where the impact is a minor loss of efficiency for worker elevator travel. Significant adjustments may be necessary for exterior cladding repairs on a high-rise building which could require significant scaffolding for an otherwise low cost repair item. Both of these extremes are unlikely to produce a significant total repair cost error, since they are typically combined with much less sensitive work items. While there can be a significant range of height premium costs for individual items, the aggregated modifications will be a relatively small increase for most cases. Table 2-1 presents suggested **Height Factor** premiums.

Table 2-1 Height Factor Premium Values for Building Level

Building Level	Height Factor
Below grade levels and floors 1-4	1.00
Floors 5-10	1.08
Floor 11 and higher	1.16

The **Hazmat Factor** field is used to reflect the variable hazardous material premiums. For new buildings, hazardous materials issues are generally a function of occupancy. Healthcare and research facilities typically contain some amount of hazardous material to support their operations. In many older buildings hazardous materials have been removed as part of recent tenant improvement and building modernization projects. Unless specific information is known, a **Hazmat Factor** of 1.0 is recommended. It is reasonable to expect this factor to range from 1.00 for modern buildings without significant hazardous material content to 1.20 for buildings that contain significant amounts of hazardous material including lead-based paint and asbestos. Determination of **Hazmat Factors** should consider the following:

- **Friable asbestos insulation.** This material is typically found in pipe lagging in buildings constructed in 1979 or earlier. Friable lagging could be present on all pipes in earlier construction. It was more commonly applied only to boilers, bends and tees, and irregularly shaped elements in later construction. While the cost for removal or abatement is high, the extent is typically limited. A recommended mid-point range for replacement or abatement is \$10,000 per boiler or furnace, \$50 per lineal foot of piping, or alternatively \$2 to \$3 per square foot of overall gross building area.
- **Friable asbestos fireproofing.** This material is typically found in sprayed-on structural steel fireproofing in buildings constructed from the 1940s through the 1970s. Recommended midpoint cost for removal or abatement is \$20,000 per location of steel repair, \$15 to \$25 per square foot of overall gross building area (based on 100% abatement).
- **Non-friable asbestos cement products.** These products are typically found in flooring, siding or roofing of buildings but may be present in limited quantities in fire protection. The cost of removal or abatement is unlikely to be a significant factor in the repair costs for low to moderately damaged buildings.
- **Asbestos containing materials.** These materials are common in buildings constructed from the 1940s through the 1970s and could be present in earlier buildings. Asbestos containing materials are pervasive and can be found in ceiling tiles, spray acoustic treatment, flooring materials, floor mastic, roofing materials, caulk, and drywall taping compound. A recommended cost for removal or abatement is approximately \$10 to \$30 per square foot of overall gross building area.
- **Polychlorinated biphenols.** This material is commonly found in electrical equipment that includes fluorescent light ballasts and caulk. Polychlorinated biphenols (PCB) could be present in buildings constructed before 1991, but are more likely present in construction preceding 1980. In many cases, PCB ballasts have been replaced during energy retrofits, so older buildings may not necessarily contain PCB materials.

The following midpoint costs for removal or abatement are suggested:

- \$100 per ballast for replacement in damaged fixtures. Ballasts in undamaged fixtures should not need to be replaced following an earthquake.

- Premium cost of \$20,000 per item (in addition to equipment replacement) of other electrical equipment (transformers, switchgear).
- Caulk containing PCB has only recently been recognized as a significant environmental problem. Repair protocols are not well established. PCB can migrate from the caulk into surrounding porous materials. This could necessitate not only caulk removal, but also replacement of surrounding materials, such as masonry, concrete, or wood. The midpoint costs suggested are for recaulking only and for abatement or removal is \$15 per lineal foot or \$3 to \$5 per square foot of overall gross building area.
- **Lead based paint.** In buildings constructed prior to 1980 painted surfaces, particularly wood and steel, are likely to contain lead based paint. Midpoint cost for removal or abatement is \$3 per square foot of painted area, or \$2 to \$5 per square foot for multi-unit residential and education facilities, and \$5 to \$8 per square foot of overall building area for complete structural steel abatement. For structural steel, \$5,000 per repair location may be used.

There are many other hazardous materials and conditions that could be encountered in repair efforts. In the larger context of seismic repair, typically these treatments are inconsequential from a cost perspective. These materials can include mercury in light fixtures and switching devices (thermostats), dry-cleaning fluids, gasoline, diesel or other hydrocarbons in generators or fuel storage tanks, chemicals from process or manufacturing, and radioactive materials (particularly in healthcare or laboratory equipment).

The **Occupancy Factor** reflects the added cost of working around ongoing building operations, equipment, and the collateral protections required for some construction characteristics. The repair premium is significantly more pronounced in occupied buildings than in vacated buildings. However, the level of collateral protection required even in an unoccupied building may be significant. Table 2-2 lists recommended repair premiums for typical occupied and unoccupied buildings. PACT does not presently distinguish between occupied and unoccupied repair conditions.

For time-based assessments, “unoccupied” factors should be used. For scenario- and intensity-based assessments, “occupied” factors should be used for low intensity shaking since repair of minor damage is likely to be done while the building is occupied. For moderate to high intensity shaking, the

use of the “unoccupied” factors is recommended, as buildings are more likely to be damaged beyond a level at which repair during occupancy is practical.

Table 2-2 Occupancy Factors

Occupancy Category	Occupancy Factor	
	Unoccupied	Occupied
Commercial Office	1.0	1.2
Research	1.4	1.8
Healthcare	1.5	2.0
Education K-12	1.0	1.1
Multi-Unit Residential	1.1	1.2
Retail	1.2	1.3
Warehouse	1.1	1.1
Hospitality	1.1	1.3

2.2.3 Population Model

To assess casualties, users must define the population model, i.e., the distribution of occupants within the building at various times of day. In PACT, it is possible to use one of the provided building population models or to develop and input building-specific models. Eight population models are provided in PACT corresponding to typical commercial office, education K-12 (elementary, middle, high school), healthcare, hospitality, multi-unit residential, research, retail, and warehouse occupancies.

Users can assign separate population models to several fractions of each floor level. Each population model includes the hourly distribution of people per 1,000 square feet for weekdays or weekends and can be adjusted to include further variation by month. Provided population models can be used directly or be modified to reflect the unique occupancy characteristics of a specific building, if known. Figure 2-5 illustrates the commercial office occupancy provided in PACT. Building-specific population information can be developed and modified using the **Population Manager** utility, as illustrated in Figure 2-6. The provided population models for each occupancy category can be viewed by selecting from the column on the left and modified by substituting data on the right side of the window. New occupancy models can be created by overwriting the existing ones or creating new names for the occupancy.

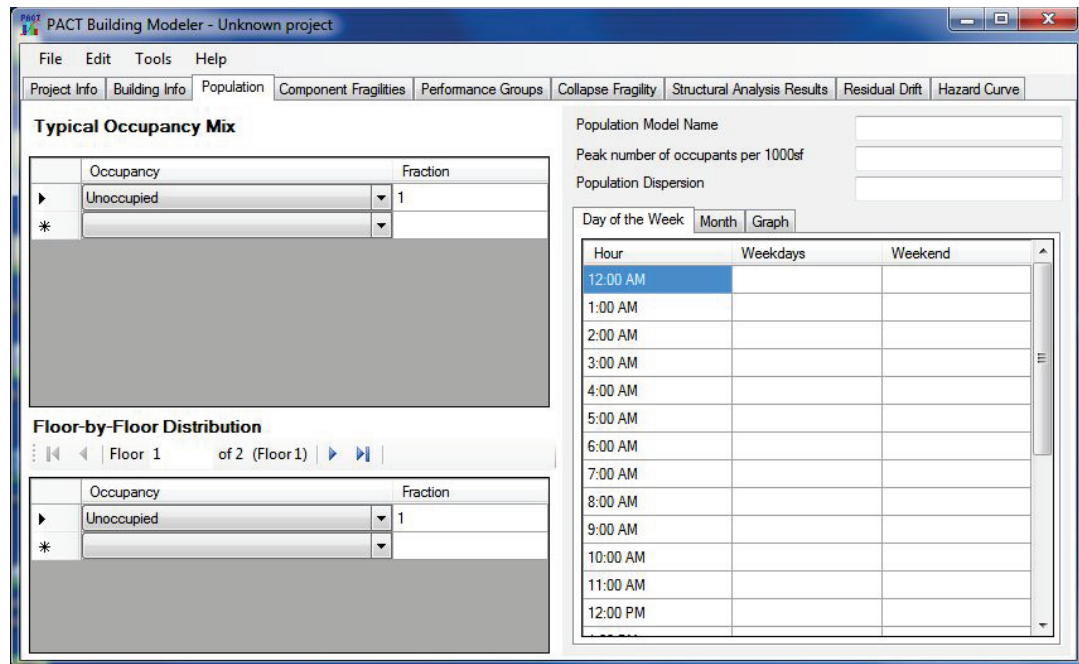


Figure 2-5 PACT Population tab showing commercial office occupancy.

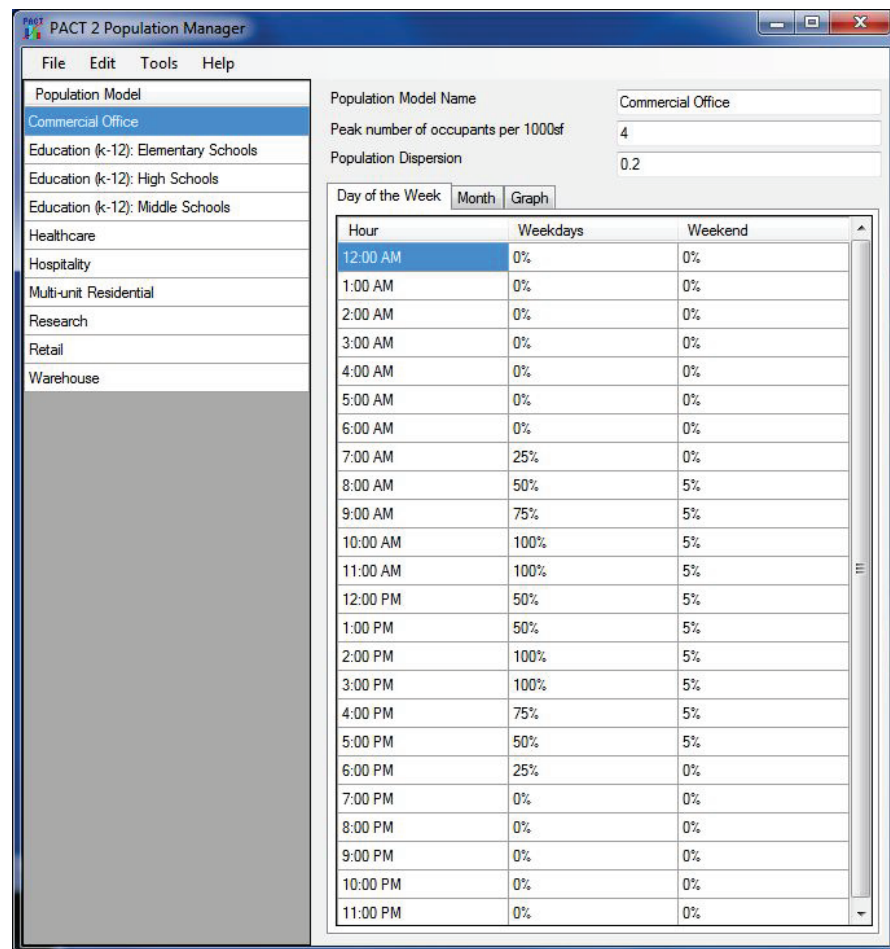


Figure 2-6 PACT Population Manager utility.

2.3 Fragility Specifications and Performance Groups

Following the definition of the general building characteristics, it is necessary to define the quantity, vulnerability, and distribution of damageable components and contents. PACT organizes this process into two parts: (1) identification of required fragility specifications for each floor, and (2) identification of the quantity of components in each performance group at each floor.

The fragility specification includes a description of the demand parameter that predicts damage, the types of damage that can occur, fragility functions, which indicate the probability of incurring each damage state as a function of demand, and consequence functions, which indicate the probable values of loss that will occur as a result of each damage state.

Each fragility function specifies damage state probabilities for a single demand parameter. Typically, peak story drift ratio or peak floor acceleration parameters are used to determine if a component is damaged. The demand parameter can have a specific orientation with respect to the component (directional demand) or the demand can be non-directional. For example, wall elements will typically be damaged by story drift within their plane, where suspended ceiling systems are susceptible to damage from floor acceleration independent of horizontal direction. Users should be aware that floor acceleration important to the damageability of a component, such as ceiling mounted nonstructural components, may be associated with the floor level above the level under consideration. Unanchored nonstructural components use peak total floor velocity as the demand parameter.

User-defined, building-specific fragility functions can use any appropriate demand parameter. For example, a user could decide that beam-column joint plastic rotation is the best predictor of damage for a particular type of structural component and could develop fragility functions based on that parameter. If demand parameters other than story drift ratio, floor acceleration, or velocity are used, the structural analysis used to estimate building response must provide values for the selected demand parameters.

The quantity and distribution of damageable components conforming to each selected fragility specification is entered into PACT through the definition of performance groups at each floor level. A performance group is a set of components described by a single fragility group that will experience the same demand. Performance groups are ordered by the direction of application of their common demand parameter.

In PACT, components can be selected and distributed across the building's floors to create a complete representation of the damageable building. To

determine the quantities of vulnerable nonstructural components and contents within a building, the *Normative Quantity Estimation Tool* provided in Volume 3 can be utilized.

Users should be aware that the list of component fragility specifications provided with PACT does not include all vulnerable building components that may be present in a building. Users must carefully identify damageable building features not provided in PACT. User-defined fragility and consequence functions can be developed following the guidance provided in Chapters 6, 7, and 8.

2.3.1 Fragility Specifications Provided in PACT

PACT references a data set of more than 700 individual fragility specifications, containing both structural and nonstructural components, contained in the *Fragility Database* provided as part of Volume 3. Table 2-3 provides a list of fragility groups identified in PACT where fragility groups with fragility specifications provided in PACT are indicated with bold lettering. Figure 2-7 illustrates the PACT window used to select fragility groups present in a performance model.

Each fragility group is identified by a unique identification code based on recommendations contained in NISTIR 6389 Report, *UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating and Cost Analysis*, (NIST, 1999) where codes take the form: A1234.567. The first letter in the classification system indicates the overall component category. The first two numbers provides the next categorization. For instance, B10 represents superstructure components while B20 represents exterior enclosures. The next two numbers identify a unique component. For example, the classification for reinforced concrete shear walls is B1044. The identifiers after the decimal provide variations of the basic component and are used to identify different configurations, conditions of installation, material quantities, demand levels, and other attributes.

Note that many building components are inherently rugged and not subject to significant damage for credible levels of demand. Rugged components include such things as plumbing fixtures, electrical raceways, wall-mounted panels, and some components of gravity framing systems. Volume 1, Appendix I provides an itemized listing of common building components that can generally be considered rugged. These components are not typically susceptible to damage as a result of a building's earthquake response and need not be included in the building performance model.

Table 2-3 Fragility Groups in PACT

Component Category	Component Name
A	Substructure
A10	Foundations
A101	Standard Foundations
A102	Special Foundations
A103	Slab on Grade
A20	Basement Construction
A202	Basement Walls
B	Shell
B10	Super Structure
B101	Floor Construction
B102	Roof Construction
B103	Structural Steel Elements
B104	Reinforced Concrete Elements
B105	Masonry Vertical Elements
B106	Cold-Formed Steel Structural Elements
B107	Wood Light Frame Structural Elements
B20	Exterior Enclosure
B201	Exterior Nonstructural Walls
B202	Exterior Window Systems
B203	Exterior Doors
B30	Roof Elements
B301	Roof Coverings
B302	Roof Openings
B303	Masonry Chimney (residential)
B304	Masonry Parapet
B40	Exterior Finishes
B401	Exterior Finishes
C	Interiors
C10	Interior Construction
C101	Partitions
C102	Interior Doors
C20	Stairs
C201	Stairs

Table 2-3 Fragility Groups in PACT (continued)

Component Category	Component Name
C30	Interior Finishes
C301	Wall Finishes
C302	Floor Finishes, Raised Access Floors, and Floor Flooding
C303	Ceilings and Ceiling Lighting
D	Services
D10	Conveying
D101	Elevators and Lifts
D102	Escalators and Moving Walks
D103	Other Conveying Systems
D20	Plumbing
D202	Domestic Water Distribution including hot water heaters
D203	Sanitary Waste Piping System
D204	Rain Water Drainage Piping System
D205	Chilled Water Piping
D206	Steam Piping
D209	Other Piping
D30	HVAC
D301	Energy Supply
D302	Heat Generating Systems (furnaces and boilers)
D303	Chillers, Cooling Towers, and Compressors
D304	Distribution Systems including Fans, Drops and Diffusers, and VAV Boxes
D305	Packaged Air Handling Units
D306	Control Panels and Instrumentation
D309	Other HVAC Systems and Equipment
D40	Fire Protection
D401	Sprinkler Horizontal Distribution including Risers and Drops
D402	Standpipes
D403	Fire Protection Specialties
D409	Other Fire Protection Systems
D50	Electrical
D501	Electrical Service & Distribution
D502	Lighting and Branch Wiring
D503	Communications and security
D509	Other Electrical Systems including Generators, Battery racks, and Chargers

Table 2-3 Fragility Groups in PACT (continued)

Component Category	Component Name
E	Equipment & Furnishings
E10	Equipment
E101	Commercial Equipment
E102	Institutional Equipment
E103	Vehicular Equipment
E109	Other Equipment
E20	Furnishings
E201	Fixed Furnishings
E202	Movable Furnishing, including Office Furniture and Equipment
F	Special Construction and Demolition
F10	Special Construction
F101	Special Structures including Storage Racks
F103	Special Construction Systems
F104	Special Facilities
F105	Special Controls and Instrumentation

PACT Building Modeler - Unknown project

File Edit Tools Help

Project Info Building Info Population **Component Fragilities** Performance Groups Collapse Fragility Structural Analysis Results Residual Drift Hazard Curve

Most Typical Specifications

Category	Component	Dir. 1	Dir. 2	Population Model
A: Substructure		<input type="checkbox"/>	<input type="checkbox"/>	
A10: Foundations		<input type="checkbox"/>	<input type="checkbox"/>	
A101: Standard Foundati...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
A102: Special Foundations	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
A103: Slab on Grade	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	

Floor-by-Floor Distribution

... || Floor 1 of 2 (Floor 1) || ...

Category	Component	Dir. 1	Dir. 2	Population Model
A: Substructure		<input type="checkbox"/>	<input type="checkbox"/>	
A10: Foundations		<input type="checkbox"/>	<input type="checkbox"/>	
A101: Standard Foundati...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
A102: Special Foundations	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
A103: Slab on Grade	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
A20: Basement Construc...		<input type="checkbox"/>	<input type="checkbox"/>	
A202: Basement Walls	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B: Shell		<input type="checkbox"/>	<input type="checkbox"/>	
B10: Super Structure		<input type="checkbox"/>	<input type="checkbox"/>	

Figure 2-7 PACT Component Fragilities tab showing fragility specification selection.

2.3.2 Demand Directionality

Users must identify whether components are sensitive to a direction of shaking. Vertical elements of the seismic-force-resisting system, including frames and walls are generally susceptible to damage from in-plane shaking. Distributed slab column systems can be damaged by drifts along either building axis. These components should be treated as possessing non-directional fragility specifications.

Many nonstructural components are assumed to be vulnerable to damage independent of shaking direction. Damage to nonstructural components may be a function of story drift ratio, floor velocity, or floor acceleration. While some components may actually be damaged by a combination of drift, floor acceleration, and velocity, the methodology only permits use of a single demand parameter for damage prediction.

2.4 Identification of Vulnerable Structural Components and Systems

In addition to elements of a structure's intended seismic-force-resisting system, damageable structural components should include vulnerable structural elements normally considered part of the vertical-force-resisting system.

Appendix A lists the structural fragility specifications provided in the *Fragility Database* referenced by PACT, organized into five component categories, spanning the range of structural materials from structural steel to wood light frame systems.

Each component category contains multiple fragility specifications, which reflect a range of configuration and construction variations affecting seismic performance characteristics, such as special and ordinary masonry walls. PACT makes further differentiation among some components with identical damageability but with significant differences in damage state consequences, such as repair costs, owing to such characteristics as size and finish.

Users should select the most appropriate set of structural fragility specifications using the descriptions provided in PACT for each principal building direction. The PACT **Fragility Specification Manager** utility can also facilitate the process of identifying appropriate fragility specifications. This utility presents general information on the provided fragility specifications and includes a summary of the demand parameter and characterization of its applicability to demand directionality and also permits modification of fragility specifications and definition of new ones.

Fragility specifications for horizontal floor or roof construction components or systems acting as diaphragms are not provided. However, fragility information for some diaphragm components that act as part of the vertical-force-resisting system such as slab-column joints and steel beam shear tab connections, is included, as shown in Appendix A. For buildings with damageable diaphragms, the user must generate fragility and consequence functions using either laboratory data or calculations. For further guidance see Chapter 6 and Chapter 8.

The following sections discuss the general categories of superstructure components included for each of the provided fragility specifications. Appendix A provides a summary of construction design characteristics, information on damage mode, design configuration, and other features, organized by the fragility classification numbers.

2.4.1 Structural Steel Elements (B103)

This fragility classification (B103) is summarized in Table A-1 and includes miscellaneous components and structural steel braced frame and structural steel moment frame systems.

Miscellaneous components include gravity beam connections that feature a bolted shear tab (B1031.001) and column base plates, differentiated by column weight as follows:

- B1031.011a: Columns \leq 150 plf
- B1031.011b: 150 plf < Columns \leq 300 plf
- B1031.011c: Columns > 300 plf

Column base plates should be included in the performance model when they are part of the lateral force-resisting system and are designed to provide rotational restraint at the base.

Also within this component category are three fragility specifications for welded column splices, again differentiated by column weight:

- B1031.021a: Columns \leq 150 plf
- B1031.021b: 150 plf < Columns \leq 300 plf
- B1031.021c: Columns > 300 plf

Only column splices that are part of the lateral force-resisting system should be included in the performance model.

Second Edition Update
Consideration of column base plates and splices have been added.

Structural steel braced frame fragility groups include selections for concentrically braced (special and ordinary) as well as buckling-restrained and eccentrically braced and systems. For each brace type and configuration, selections are further subdivided by brace weight below, where “XXX” in the fragility classification numbers represents an integer, depending upon the subcategory represented:

- B1033.XXXa: Brace < 40 plf
- B1033.XXXb: 41 plf < Brace < 99 plf
- B1033.XXXc: Brace > 100 plf

Special concentrically braced systems (B1033.001a – B1033.043c) include those with balanced designs in which gusset plates are configured to yield in an elliptical pattern such that gusset strength coincides with brace strength (Lehman et al., 2008), tapered gussets and those conforming to AISC minimum standards. These categories are further subdivided by brace types (wide flange, HSS, double angles) and for each brace type, by configuration (chevron, single diagonal, x-diagonals).

Ordinary braced frames (B1033.051a – B1033.063c) are subdivided into three basic categories: compact braces, braces at the ductile slenderness limit, and braces designed without specific seismic detailing. Each of these categories includes selections for chevron, single diagonal, and x-diagonal configurations that reflect wide flange, HSS, or double angle brace sections.

Braced frames designed with factored loads only with no additional seismic detailing (B1033.071a – B1033.073c) are subdivided by configuration (chevron, single diagonal, x-diagonals).

Buckling-restrained brace (BRB) frames (B1033.101a – B1033.101c) are subdivided into two categories based on their configuration (chevron braces and single diagonal braces).

Story drift ratio is the demand parameter used for all steel braced frame fragility specifications, except eccentrically braced systems. Steel braced frame systems are measured in individual units, i.e., “each,” corresponding to one bay of bracing.

Eccentrically braced frames (EBF) governed by the formation of a shear link are divided into those with floor framing supported by the link beam and those where the link beam does not support floor framing. These selections are further divided by link beam weight below, where “X” in the fragility classification numbers represents an integer, depending upon the subcategory represented:

- B1035.06Xa: Link < 100 plf
- B1035.06Xb: 100 plf < Link < 200 plf

Link rotation angle is the demand parameter used for EBF systems. This parameter can be obtained directly from response history analysis. When simplified analysis is used, link rotation angle can be estimated using the median estimate of story drift and the story yield drift. AISC 341-05, *Seismic Provisions for Structural Steel Buildings*, (AISC, 2005) Section C15.2 provides guidance for calculating link rotation angle from the story yield drift. Because the behavior of the EBF system is governed by the shear link, the braces themselves are considered rugged and are not included in the performance model. Section 3.3.2.2.2 provides guidance for estimating story yield. Section 3.3.1.3 provides guidance on input of structural analysis results.

Eccentrically braced frame systems are measured in individual units, i.e., “each,” corresponding to one bay of eccentric bracing.

Steel moment frame systems include pre-Northridge and post-Northridge categories. Post-Northridge selections are further subdivided into configurations with reduced beam sections (RBS) with welded webs and not RBS configurations. The systems are further subdivided into those with beams on one side of the column, and those with beams on both sides of the column and yet further by beam size as follows:

- B1035.001: RBS, Beam one side, Beam \leq W27
- B1035.002: RBS, Beam one side, Beam > W30
- B1035.011: RBS, Beam two sides, Beam \leq W27
- B1035.012: RBS, Beam two sides, Beam > W30
- B1035.021: Not RBS, Beam one side, Beam \leq W27
- B1035.022: Not RBS, Beam one side, Beam > W30
- B1035.031: Not RBS, Beam two sides, Beam \leq W27
- B1035.032: Not RBS, Beam two sides, Beam > W30

Pre-Northridge steel moment frame assemblies are assumed to have welded flange bolted web connections without special weld access holes or notch-through weld metal. Fragility specifications for these components are subdivided into one- and two-sided configurations and by beam size as follows:

- B1035.041: Beam one side, Beam \leq W27

- B1035.042: Beam one side, Beam > W30
- B1035.051: Beam two sides, Beam ≤ W27
- B1035.052: Beam two sides, Beam > W30

Story drift ratio is the demand parameter used for all steel moment frame fragility specifications. Beam-column moment connections are measured in individual units, i.e., “each.”

2.4.2 Reinforced Concrete Elements (B104)

This fragility classification (B104) is summarized in Table A-2 and includes reinforced concrete moment frame and shear wall systems. Reinforced concrete moment frame systems are divided into those with beam elements and those consisting of slabs acting in conjunction with columns to provide frame action.

Reinforced concrete moment frame systems with discreet beams are further subdivided into four basic categories that reflect the modes of failure anticipated based upon detailing and reinforcement proportioning. These include: special moment frame, intermediate moment frame, ordinary moment frame, and non-conforming frame systems. These systems are subdivided based on the size of the beams and the presence of beams on one side of the column or two, as illustrated in Table 2-4. In the table, “XX” represents an integer representing a moment frame subcategory.

Table 2-4 Fragility Classification for Reinforced Concrete Moment Frames

Beam Size	Fragility Classification Number	
	One Sided	Two Sided
24×24	B1041.XX1a	B1041.XX1b
24×36	B1041.XX2a	B1041.XX2b
36×36	B1041.XX3a	B1041.XX3b

Reinforced concrete special moment frame systems are subdivided into frames governed by beam yield and those with relatively weak joints. For those systems governed by beam yield, selections are further subdivided by the presence of beams on one side of the column or two and beam size, and XX in Table 2-4 is taken as 00, e.g., B1041.001a for a moment frame with 24×24 beam size with beams on one side of the column only.

For special moment frame systems judged to have relatively weak joints with $(\sum M_c / \sum M_b) > 1.2 P_u(col) < 0.6 f'_c$ and a joint shear ratio, (V/V_n) , less than 1.2 with ACI 318-11, *Building Code Requirements for Structural Concrete and*

Commentary, (ACI, 2011) compliant transverse reinforcement fragility specifications are similarly subdivided by beam size and configuration and XX in Table 2-4 is taken as 01, e.g., B1041.011a for a moment frame with 24×24 beam size with beams on one side of the column only.

Fragility classification of intermediate moment frame systems includes consideration of frame responses governed by beam-column shears and joint shear damage. Fragility specifications in this category are further subdivided by beam size and configuration and XX in Table 2-4 is taken as 02, e.g., B1041.021a for a moment frame with 24×24 beam size with beams on one side of the column only.

Ordinary moment frame systems are subdivided into 5 subcategories that reflect the governing behavior characteristics. These 5 subcategories are:

- Weak joints, beam yield (XX in Table 2-4 is taken as 03)
- Weak joints, column yield or joint shear yield (XX in Table 2-4 is taken as 04)
- Beam yield (flexure or shear) with weak joints (XX in Table 2-4 is taken as 05)
- Column yield with strong joints (XX in Table 2-4 is taken as 06)
- Weak columns with high axial loads and strong joints (XX in Table 2-4 is taken as 07)

Selections from among these subcategories can be made by reviewing the strength ratios and notations in column 4 of Table A-2. Each subcategory is further subdivided by beam size and configuration.

Non-conforming moment frame systems include 6 subcategories based on anticipated behavior characteristics. These 6 subcategories are:

- Weak joints, beam yield (XX in Table 2-4 is taken as 08)
- Weak joints, column yield (XX in Table 2-4 is taken as 09)
- Weak beams, strong joints (XX in Table 2-4 is taken as 10)
- Weak columns, low to moderate axial loads (XX in Table 2-4 is taken as 11)
- Weak columns, strong joints, high axial loads (XX in Table 2-4 is taken as 12)
- Inadequate reinforcement development (beam or column) (XX in Table 2-4 is taken as 13)

Selections from among these subcategories can be made by reviewing the strength ratios and notations in column 4 of Table A-2. Each subcategory is further subdivided by beam size and configuration.

Story drift ratio is the demand parameter used for all reinforced concrete moment frames. Beam-column moment connections are measured in individual units, i.e., “each.” For moment frames with beams, separate performance groups must be designated in each direction.

Slab-column joints in flat slab systems are subdivided into the following 5 categories:

- Flat slab without shear reinforcement at columns (B1049.001a – B1049.003b)
- Flat slab with shear reinforcement at columns (B1049.011 – B1049.012)
- Post-tensioned slab without shear reinforcement at columns (B1049.021a – B1049.022b)
- Post-tensioned slab with shear reinforcement at columns (B1049.031 – B1049.032)
- Flat slab with drop panel or capital without shear reinforcement at columns (B1049.041a – B1049.042b)

Each of these subcategories is further subdivided by the ratio of gravity shear to total shear (factored) and whether integrity reinforcement over columns is present or not. This results in 18 selections that encompass classification numbers B1049.001a through B1049.042b.

Story drift ratio is the demand parameter used for all reinforced concrete moment frames. Slab-to-column connections are measured in individual units, i.e., “each.” Slab-column moment frame fragility specifications use non-directional demands.

Reinforced concrete shear wall systems include concrete link beams, low aspect ratio walls (aspect ratio < 1.0), low-rise walls, and slender walls (aspect ratio ≥ 2.0). Reinforced concrete wall systems are measured in units of $H \times H$ panels, where H is the height of the panel. Concrete link beams are subdivided based on their reinforcement (diagonal or conventional, and further subdivided based on the aspect ratio of the link beam and the sizes of the beam and column. This results in 12 selections that encompass classification numbers B1042.001 – B1042.022b.

Nine subcategories of low aspect ratio walls reflect reinforcement and configuration options (single curtain or double curtain of reinforcement and

the presence of flanges or boundary columns), wall thickness, and height. Planar single curtain walls include walls 8 inches thick or less at heights including 15 feet, 16-24 feet or 25-40 feet corresponding to fragility classification numbers B1044.001, B1044.002 and B1044.003. Table 2-5 indicates the fragility categories available for concrete walls with two curtains of reinforcement. Story drift ratio is the demand parameter for low aspect ratio reinforced concrete wall systems.

Table 2-6 indicates the further sub-categorization of wall fragility specifications to account for configurations with return flanges including single curtain and double curtain reinforcement subcategories thickness and height subdivisions:

Table 2-5 Fragility Classification for Low Aspect Ratio Reinforced Concrete Walls with Two Curtains of Reinforcement

Thickness	Height	Fragility Classification Number
8-16 inches	≤ 15 feet	B1044.011
8-16 inches	16 to 24 feet	B1044.012
8-16 inches	25 to 40 feet	B1044.013
17-24 inches	≤ 15 feet	B1044.021
17-24 inches	16 to 24 feet	B1044.022
17-24 inches	25 to 40 feet	B1044.023

Table 2-6 Fragility Classification for Reinforced Concrete Walls with Return Flanges

Curtains of Reinforcement	Thickness	Height	Fragility Classification Number
Single	≤ 8 inches	≤ 15 feet	B1044.031
		16 to 24 feet	B1044.032
		25 to 40 feet	B1044.033
Double	8-16 inches	≤ 15 feet	B1044.041
		16 to 24 feet	B1044.042
		25 to 40 feet	B1044.043
	17-24 inches	≤ 15 feet	B1044.051
		16 to 24 feet	B1044.052
		25 to 40 feet	B1044.053

Similar to walls with flanges, walls with boundary columns are subdivided into categories that reflect single and double curtains of reinforcement,

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Effective drift was introduced as the demand parameter for reinforced concrete slender wall systems.

further subdivided by thickness and height. This results in 12 selections that encompass classification numbers B1044.061 – B1044.083.

Slender walls (with height to length ratios in excess of 2) are subdivided by thickness (12, 18, and 30 inches) and further subdivided by wall length (15, 20, and 30 feet). This results in 9 selections that encompass classification numbers B1044.091 – B1044.113.

Effective story drift ratio is the demand parameter for reinforced concrete slender wall systems.

2.4.3 Reinforced Masonry Elements (B105)

This fragility classification (B105) is summarized in Table A-3 and includes fully grouted and partially grouted reinforced masonry walls. Each of these categories is further subdivided into shear dominated or flexure dominated behavior. Shear dominated walls will fail in shear rather than yield in flexure. Flexure dominated walls have sufficient shear strength to force flexural hinging of the wall as a limit state. ACI 530-08, *Building Code Requirements for Masonry Structures and Specifications for Masonry Structures*, (ACI, 2008) equations can be used to establish the appropriate subcategory selection. Within these subcategories (shear or flexure dominated) further subdivisions are made based on wall thickness and height as shown in Table 2-7.

Table 2-7 Fragility Classification for Reinforced Masonry Walls

Construction Characteristics	Damage Mode	Thickness	Height	Fragility Classification Number
Partially Grouted	Shear dominated	4-6 inches	≤ 12 feet	B1051.001
			> 12 feet	B1051.002
		8-12 inches	≤ 12 feet	B1051.011
			> 12 feet	B1051.012
		16 inches	≤ 12 feet	B1051.021
			> 12 feet	B1051.022
	Flexure dominated	4-6 inches	≤ 12 feet	B1051.003
			> 12 feet	B1051.004
		8-12 inches	≤ 12 feet	B1051.013
			> 12 feet	B1051.014
		16 inches	≤ 12 feet	B1051.023
			> 12 feet	B1051.024

Table 2-7 Fragility Classification for Reinforced Masonry Walls (continued)

Construction Characteristics	Damage Mode	Thickness	Height	Fragility Classification Number
Fully Grouted	Shear dominated	8-12 inches	≤ 12 feet	B1052.001
			> 12 feet	B1052.002
		16 inches	≤ 12 feet	B1052.011
			> 12 feet	B1052.012
	Flexure dominated	8-12 inches	≤ 12 feet	B1052.003
			> 12 feet	B1052.004
		16 inches	≤ 12 feet	B1052.013
			> 12 feet	B1052.014

Story drift ratio is the demand parameter used for masonry walls. Reinforced masonry walls are measured in units of $H \times H$ panels, where H is the height of the panel.

2.4.4 Cold-Formed Steel Structural Elements (B106)

This fragility classification (B106) is summarized in Table A-4 and includes repetitively framed wall systems that derive lateral resistance from wood panel siding, flat strap x-bracing, and steel sheathing. Sufficiently strong holdowns are assumed so that damage arises in the fasteners, studs, and sheathing. Subcategories for these basic fragility specifications are included to reflect performance of walls with stucco on one side (exterior). This results in 6 selections that encompass classification numbers B1061.001a – B1061.021b. Fragility specifications for interior walls with gypsum board finishes (partitions) can be found in Section 2.5.4 and Table B-4.

Story drift is the demand parameter for cold-formed steel wall systems. Cold-formed steel wall systems are measured in units of $H \times H$ panels, where H is the height of the panel.

2.4.5 Wood Light Frame Structural Elements (B107)

This fragility classification (B107) is summarized in Table A-5 and includes repetitively framed walls with structural panel sheathing, gypsum board sheathing, and let-in diagonal strut bracing. Structural panel sheathing includes oriented strand board (OSB) or plywood. Fragility specifications are provided for systems with and without holdowns for systems with stucco, and for double side gypsum board sheathed walls without holdowns. This results in 5 selections that encompass classification numbers B1071.001 – B1071.031. Fragility specifications for wood stud walls with single sided gypsum board only (partitions) can be found in Section 2.5.4 and Table B-4.

The wall fragility specifications provided are applicable to wall piers with height to length ratios up to 2.0. For ratios from 2.0 to 3.5, users can adapt the fragility specifications provided using the **PACT Fragility Specification Manager** utility. This adaptation requires scaling the median value of each damage state by the ratio $2L/H$, where L is the wall length, and H is the wall height. Section 6.3 provides guidance on the input of user defined fragility information.

Table B-6 provides finish specifications for light framed walls. Finishes are identified as individual components for input of fragility specification and performance group assignment.

Story drift ratio is the demand parameter for wood light frame systems. Wood light frame systems are measured in units of $H \times H$ panels, where H is the height of the panel.

2.4.6 Structural Performance Groups

After identifying the fragility groups present, it is necessary to distribute these into individual performance groups and populate these groups with the quantities of components present in each.

Structural performance groups are entered into PACT on a floor-by-floor basis for each of: direction 1, direction 2, and non-directional, as appropriate. A performance group of like components should be assembled for all elements resisting earthquake deformation in each direction at each floor.

For steel and reinforced concrete moment frames, the number of interior (beams framing to both sides of the column) and exterior (beams framing to one side of the column) joints is input for each direction on each floor. For steel braced frames, the number of bays of framing is the quantity used.

Flat slab column joints are susceptible to damage associated with the maximum story drift ratio in any horizontal direction. Such components are defined in PACT as non-directional.

For wall systems, the unit of measure is the number of panel elements active in a particular direction of response. For example, low aspect ratio shear walls are measured in units of $H \times H$ panels because damage in these walls often occurs in the form of diagonal “X” pattern cracking extending across panels of this size. For a building with a 36 foot long wall and 12 foot story height, the number of panels input into PACT would be three (36ft/12ft) in that direction.

Slender walls having aspect ratios greater than 2:1 typically exhibit flexurally-controlled behavior resulting in damage occurring predominantly in a flexural hinge region at the base of the wall. Aspect ratio is defined as the overall length of the wall divided by its length. The flexural hinge region is typically taken as the greater of one half the wall height or a single story height. Given that these walls generally only exhibit flexural damage in the hinge region, structural performance groups need only be defined at these floor locations. If secondary hinges or shear damage are anticipated at other levels of the building due to higher mode effects or changes in the wall geometry, structural performance groups for these stories should also be defined. Other portions of the wall need not be included since damage is not anticipated.

If performance group members are identified as “correlated,” PACT will determine a single damage state for each realization that applies to all members of the performance group. If performance group members are identified as “uncorrelated,” PACT will independently evaluate the damage state for each member of the group on the basis of the demand value and the component’s fragility function. Designating performance groups as correlated can achieve a significant reduction in data handling time and required computer disc space. There will, however, be a significant loss of variability in the resulting assessment. By selecting an uncorrelated relationship among group members, greater variability can be expected in the outcome of each realization; however, the mean consequences can be expected to be similar to the result if the members are considered as correlated. If the distribution of loss is important to the user, performance groups should be identified as uncorrelated. When casualty and unsafe placard postings are selected as performance measures, the user should not use correlated components in a performance group, unless there is reason to believe that behavior really is correlated. For example, a series of identical braces along line framing can be considered correlated because all braces will experience the same deformation and one brace cannot exhibit significant buckling deformation unless all of the braces in this line do as well. In general, components should be considered uncorrelated unless other compelling reasons exist for a correlated designation.

Figure 2-8 illustrates structural performance group selections for direction 1 on the first floor of a two-story building. Special reinforced masonry shear walls (B1052.003) have been identified with a quantity of 12.8 units. This quantity is number of $H \times H$ panels. For this example, the story height is 10 feet; therefore, the quantity reflects 128 feet of 10 foot high masonry wall in direction 1. Note that for uncorrelated components, PACT considers only

integer values of these quantities. If non-integer quantities are input, PACT will round these to the nearest integer.

No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1052.003	Special reinforced masonry walls with fully grouted cells, 8...	12.80	0.00	<input type="checkbox"/>	Research	Story Drift Ratio
B1052.003	Special reinforced masonry walls with fully grouted cells, 8...	0.00	0.00	<input type="checkbox"/>	None	Story Drift Ratio
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height...	0.00	0.00	<input type="checkbox"/>	None	Story Drift Ratio
C1011.001a	Wall Partition, Type: Gypsum with metal studs, Full Height...	11.32	0.00	<input type="checkbox"/>	Research	Story Drift Ratio
C2011.001a	Prefabricated steel stair with steel treads and landings wit...	1.00	0.00	<input type="checkbox"/>	Research	Story Drift Ratio
C3011.002c	Wall Partition, Type: Gypsum + Ceramic Tile, Full Height, ...	0.00	0.00	<input type="checkbox"/>	None	Story Drift Ratio
C3011.002c	Wall Partition, Type: Gypsum + Ceramic Tile, Full Height, ...	0.67	0.00	<input type="checkbox"/>	Research	Story Drift Ratio
D3052.011a	Air Handling Unit - Capacity: <5000 CFM - Unanchored e...	0.00	0.00	<input type="checkbox"/>	None	Acceleration
D3052.011a	Air Handling Unit - Capacity: <5000 CFM - Unanchored e...	5.00	0.00	<input type="checkbox"/>	Research	Acceleration
D3052.013b	Air Handling Unit - Capacity: <5000 CFM - Equipment that...	0.00	0.00	<input type="checkbox"/>	None	Acceleration
D3052.013b	Air Handling Unit - Capacity: <5000 CFM - Equipment that...	5.00	0.00	<input type="checkbox"/>	Research	Acceleration
D5012.023d	Low Voltage Switchgear - Capacity: 350 to <750 Amp - E...	0.00	0.00	<input type="checkbox"/>	None	Acceleration

Figure 2-8 PACT Performance Groups tab.

2.5 Identification of Vulnerable Nonstructural Components and Systems

Appendix B lists the nonstructural fragility specifications provided in the *Fragility Database* referenced by PACT, organized into 25 component categories, spanning the range of exterior curtain wall window systems to desktop electronics.

Each component category contains multiple fragility specifications, which reflect a range of configuration and material variations affecting seismic performance characteristics. PACT makes further differentiation among some components with identical damageability but with significant differences in damage state consequences, such as repair costs, owing to such characteristics as size and finish.

User-defined fragility specifications can be added as needed or existing specifications can be modified using the PACT **Fragility Specification Manager** utility. The 25 groups of nonstructural components and systems reflect the range of damageable items generally found in buildings. Users should trace an organized path that will comprehensively define the damageable nonstructural building components and systems.

There are many components for which fragility specifications are not provided. Users can develop fragility functions for these items using the guidance provided in Volume 1, Section 3.8. Chapter 7 provides guidance on development of nonstructural component fragility parameters by

calculation and Chapter 8 provides guidance for development of consequence functions.

2.5.1 Exterior Nonstructural Walls (B107 and B201)

This fragility classification (B107 and B201) is summarized in Table B-1 and includes the following types of exterior nonstructural walls:

- Gypsum with wall studs (B1071.041).
- Cold-formed steel walls (B2011.001a – B2011.021b). These specifications are the same as those in category B106.
- Wood light frame walls (B2011.101 – B2011.131) with structural panel sheathing, gypsum board sheathing, and let-in diagonal strut bracing. These specifications are the same as the wood light frame walls in category B107.
- Precast concrete cladding panels (B2011.201a – B2011.201b).

For walls in this category, damageability is often a function of detailing.

2.5.1.1 Perimeter Cladding Systems

Fragility and consequence functions for these systems should include consideration of the size of the gap provided in the panel system to accommodate horizontal drift. The in-plane distortion required to bring adjacent panels into contact can be converted to an equivalent story drift using the geometry of the panel. Contact points can occur at the panel corners and at the interface with column cover panels. System suppliers often can indicate the amount of drift that can be accommodated before adjacent panels contact. The design story drift for the structure should be used for estimating the drift accommodation ratios of cladding systems. If this unknown, Table 2-8 provides guidance for commonly constructed gap sizes as a function of building category (according to ASCE/SEI 7) and the operative design code for the period of construction. The table expresses the gap in terms of story drift ratio.

Table 2-8 Suggested Drift Accommodation Ratio δ_a

Building Code	Building Occupancy Category per ASCE/SEI 7		
	II	III	IV
1994 UBC (ICC, 1994) or before	0.012	0.012	0.012
1997 UBC (ICC, 1997)	0.020	0.020	0.020
2000 IBC (ICC, 2000) – 2009 IBC (ICC, 2009)	0.020	0.015	0.010
2012 IBC (ICC, 2012) or thereafter	0.020	0.019	0.015

In-plane story drift ratio is the demand parameter for perimeter cladding systems. The area of cladding per floor is dependent on the floor perimeter in each direction and the height of the floor (less the area of glazing). Perimeter cladding systems are measured in units of 100 square feet, i.e., the net cladding area (in square feet) in each direction between floors divided by 100.

Perimeter cladding systems may also be vulnerable to damage when out-of-plane floor accelerations or drifts exceed the component or anchorage capacity. To avoid double counting damage to the same component, only the specification for the governing demand should be input to the assessment model. In cases where vulnerability to in-plane and out-of-plane demands is comparable, some of the components can be assigned to one performance group having in-plane vulnerability, and the balance to a second group having out-of-plane vulnerability.

2.5.1.2 Precast Concrete Cladding Panels

Two fragility specifications are provided for precast concrete cladding panels (B2011.201a and B2011.201b). One is associated with damage in-plane while the other fragility is associated with out-of-plane damage. Users must provide the median demand and dispersion values based on the details of the system present.

Unless panel detailing indicates greater capacity, it is suggested that the median in-plane demand requiring panel replacement be taken as $(\delta_a + 0.005)$ where δ_a is the code design story drift used for the precast cladding system, or if this unknown, the suggested drift accommodation as indicated in Table 2-8. A dispersion value of 0.50 is suggested.

Peak floor acceleration in the direction normal to the wall at the top floor adjacent to a panel is the demand parameter used for out-of-plane damage. Section 7.3 provides guidance on the calculation of anchorage fragilities. For most situations, a crude but adequate calculation can be made by using the code seismic design acceleration coefficient for which the anchorage was presumed to be designed (see Section 7.3.1) and converting this to a median estimate of capacity. Precast concrete cladding panels are measured in units of 30 lineal feet.

Failure of precast concrete cladding has no life safety consequences within PACT because the exterior population model is unknown.

2.5.2 Exterior Window Systems (B202)

This fragility classification (B202) is summarized in Table B-2 and includes exterior window systems. The specifications are based on testing of modern metal framed exterior window systems. Testing was performed on glazing with square cut corners (the most common form of exterior window construction).

A total of 48 fragility specifications are provided, and encompass classification numbers B2022.001 through B2023.011. Forty-four of these fragilities reflect specific glazing installation details while four are provided for situations when the glazing installation detail is not defined and represents a composite of all possible details.

Fragility data for two basic window system types are provided: curtain wall systems and storefront systems. Both are for window systems supported and contained within aluminum framing.

Twenty-eight of the fragility specifications are provided for site-built (mid-rise stick built) curtain wall systems, which is the most common form of construction in the commercial building industry and for which most testing has been performed. The site-built curtain wall system specifications are divided into 6 configuration types: non-laminated monolithic (single pane), symmetric (dual pane with equal thicknesses) insulated glazing units (IGU), asymmetric (dual pane with unequal thicknesses) IGUs, and laminated versions of each of these. These system types are further subdivided into three types of glass: annealed, heat-strengthened, and fully-tempered. Separate specifications are provided for variations in glazing edge clearances, glazing aspect ratios, and glass thicknesses (B2022.011 through B2022.101).

One specification is provided for unitized curtain wall (B2022.201).

The storefront window system specifications are also subdivided into configuration types including: monolithic, symmetric, and asymmetric IGUs with laminated glass for some selections, with further subdivision into annealed and fully tempered glass types. Separate specifications are provided for variations in glazing edge clearances, glazing aspect ratios, and glass thicknesses (B2023.011 through B2023.058).

Particularly for existing buildings, in many situations, the details of glazing installation may not be known. Four additional fragility specifications have been provided for these situations. Two of these are for curtain wall systems, one for monolithic, and one for IGU glazing, B2022.001 and B2022.002,

respectively. There is no subdivision for laminated glazing. It is assumed that the glazing aspect ratio is 6:5. The glazing edge clearance and glass thicknesses are assumed as unknown and variations are incorporated into the provided specifications. Similarly, two fragility specifications are provided for generic storefront window systems, B2023.001 and B2023.002.

The fragility information provided is based on the size of glazing panels tested. The median drifts associated with the damage states should be adjusted if smaller or larger glazing panels are used and gap clearances are basically the same as those for which fragilities are provided. The adjustment factor is the ratio of the tested panel height divided by actual panel height. This ratio is multiplied by the median drift value for each damage state in the specification. Table 2-9 lists the heights of tested panels for each aspect ratio.

Table 2-9 Tested Window Pane Sizes

Aspect Ratio	Tested Panel Height
6:5	6 feet
2:1	8 feet
1:2	4 feet

Where specific knowledge or details of the exterior window system is unavailable, it is suggested to use the IGU specifications with a 6:5 aspect ratio for curtain wall applications and the monolithic fragility specifications for storefront applications.

Metal panels are frequently used in conjunction with exterior window systems. Generally, the exterior window system will exhibit damage before the metal panel system. Fragility functions for the window system can be used for the combined system and the user can modify the consequence function in PACT to reflect the consequences to the entire system. Chapter 8 provides guidance on modifying consequence functions.

Story drift ratio in the plane of the wall is the demand parameter for exterior window systems. The area of glazing per floor is dependent on the perimeter length of the floor in the direction under consideration and height of the floor less the area of perimeter cladding or other non-glazed areas. The exterior window systems are measured in units of 30 square feet, i.e., the net window area (in square feet) divided by 30.

2.5.3 Roof Elements (B30)

2.5.3.1 Roof Coverings (B301)

This fragility classification (B301) is summarized in Table B-3 and includes fragility specifications for sloping roofs with concrete or clay tiles. The specifications are further subdivided based on whether the attachment to the structure is compliant with the requirements of the 1994 UBC, *Uniform Building Code*, (ICC, 1994) and later codes or not.

Peak roof acceleration (non-directional) is the demand parameter for roof coverings. Roof coverings are measured in units of 100 square feet, i.e., tiled roof area (increased for slope) in square feet divided by 100.

2.5.3.2 Unreinforced Masonry Non-Industrial Chimneys (B303)

This fragility classification (B303) is summarized in Table B-3 and includes unreinforced non-industrial masonry chimneys. The specifications are subdivided by chimney height above the roof, including: 5 feet, 10 feet, and 15 feet. Each of these categories is further subdivided into two selections that include reconstruction of the chimney with reinforced masonry or replacement with a framed alternative. Most jurisdictions no longer permit new construction using these types of chimneys in areas of significant seismic risk.

Peak roof acceleration (non-directional) is the demand parameter used for these chimneys. Chimneys are measured in individual units, i.e., “each.”

2.5.3.3 Masonry Parapets (B304)

Fragility specifications are provided for unreinforced, unbraced masonry parapets. Peak roof acceleration normal to the parapet wall is the demand parameter used for these parapets. Masonry parapets are measured in units of 100 lineal feet. As with precast cladding, failure of masonry parapets does not have any life safety consequences in PACT, although real consequences can exist.

2.5.4 Partitions (C101)

This fragility classification (C101) is summarized in Table B-4 and includes gypsum wallboard partitions on metal and wood studs.

Four subcategories of gypsum wallboard partitions on metal studs are provided: (1) full height partitions fixed to the underside of the floor at their top (C1011.001a); (2) partial height partitions sheathed with gypsum wallboard 9 feet vertically and braced to the underside of the above floor

(C1011.001b); (3) full height partitions without corners where slip track top connections restrain out-of-plane movement but not in plane horizontal or vertical movement (C1011.001c); and (4) full height partitions with slip track connections at their tops and returns at their ends (corners) (C1011.001d). It should be noted that slip track connections are often installed such that horizontal movement is restrained and therefore behave more like full-height partitions fixed to the floor above than partitions that have been designed to accommodate horizontal drift. Even when effective, slip track connections are intended to permit in-plane movement, not out-of-plane movement. As a result, such walls will behave as if they had fixed connections, particularly near intersections with other walls.

Fragilities for true “drift-protected” partition walls are not presently provided but can be added as user-defined when appropriate. The fragility and consequence functions for all four provided partition types assume gypsum wallboard on both sides of the partition and include allowances for all typical accessories including doors and embedded mechanical and electrical utilities. For damage states where the consequence includes partition replacement, the repair cost includes allowance for these accessories.

A single fragility specification (C1011.011a) is provided for full-height wood frame partitions fixed to the floor above. The fragility and consequence functions assume gypsum wallboard on both sides and include allowances for all typical accessories, including doors and embedded mechanical and electrical utilities. For damage states where the consequences include partition replacement, the repair cost includes allowance for these accessories.

It is assumed that partitions will be constructed the same regardless of finish type and will include a painted finish with taped joints. All other finishes are addressed separately under the wall finishes component category (C301) in Table B-6. The partition fragility specifications in Table B-4 must be separately included as partition walls.

Story drift ratio in the plane of the wall is the demand parameter used with partitions. Partitions are measured in units of 100 lineal feet. For estimating purposes, the walls are assumed to be 9 feet tall.

2.5.5 Stairs (C201)

This fragility classification (C201) is summarized in Table B-5 and includes four types of interior egress stairs: (1) prefabricated steel stair assemblies (C2011.001a and C2011.001b); (2) prefabricated precast concrete stair assemblies (C2011.011a and C2011.011b); (3) cast-in-place concrete stairs

(C2011.021a through C2011.021d); and (4) hybrid stairs with steel stair stringers with precast concrete treads (C2011.031a and C2011.031b). Cast-in-place concrete stairs placed monolithically with the structure should be included in the structural analysis model. Stair specifications are further subdivided based on support condition, including stairs fixed at both ends and stairs with bottom ends having slotted joints designed to accommodate story drift. For existing buildings, if the details of stair installation are not available, it is reasonable to assume the stairs are a hybrid type without slotted joints, i.e., fixed at both ends. Consequence functions are provided for all stair types.

Fragility functions are only provided for prefabricated stair assemblies (steel, precast, hybrid) composed of individual stringers, stair treads, and landings assembled without seismic joints. Fragility functions are not provided for cast-in-place and monolithic precast stairs. These components require user specified fragility functions. Chapter 6 and Chapter 7 provide guidance on developing fragility functions by calculation.

Fragility functions for stairs with seismic joints are not provided and need to be specified by the user. A suggested approach for establishing a fragility function for this condition requires estimating the story drift the joint is designed to accommodate and adding the value to the drift associated with the provided component fragility without a seismic joint.

Story drift ratio in the direction of stair alignment is the demand parameter for these systems. If the directional orientation of the stair is unknown, the demand parameter can be adjusted to non-directional. The number of stairs is based on gross square foot of building floor area and occupancy.

Volume 1, Appendix F provides quantity guidance for stairways per floor based on building floor area and occupancy. For buildings that have the same floor area at all floors, the same number of stairs should be specified at each level. Stairs are measured in individual units of stairways per floor, i.e., “each.”

2.5.6 Wall Finishes (C301)

This fragility classification (C301) is summarized in Table B-6 and includes finishes other than paint: wallpaper (C3011.001), ceramic tile (C3011.002), and high end finishes including marble or wood paneling (C3011.003).

These fragility specifications are further subdivided depending on whether the finishes are applied to partitions that are: (1) full height and fixed at the top; (2) partial height and laterally braced at the top; or (3) full height with slip track top connections.

The fragility and consequence functions assume the finish occurs on one side of the partition only, allowing different wall finishes to be specified for opposite sides of the same wall. Note that only damage states and consequences associated with damage to the finishes themselves are considered in these fragility specifications. The partitions themselves must be input separately.

Story drift ratio in the plane of the wall is the demand parameter used with wall finishes. Wall finishes are measured in 100 lineal feet of wall, similar to partitions. If both sides of a wall have finishes, the quantities should be increased accordingly.

2.5.7 Raised Access Floors and Floor Flooding (C302)

2.5.7.1 Floor Flooding

Second Edition Update
Considerations regarding floor flooding has been updated.

A fragility category is provided to account for floor flooding as a result of fire sprinkler drop or pipe leakage. Flooding fragility specifications are provided for each of the 8 occupancy types. These specifications are further subdivided based on a high or low likelihood of mold developing subsequent to the flooding. Development of mold is highly likely in geographic locations of high humidity. The flooding fragilities are non-directional.

The median demand for floor flooding is selected by the user as equal to the lowest median value of a piping component damage state included in the performance model that will result in a major leak. For Seismic Design Categories A, B, and C (no ceiling bracing) sprinkler drops will typically govern the demand selection. For Seismic Design Categories D, E, and F the demand selection is likely governed by threaded water piping.

Flooding damage is presumed to occur on only the floor where the major leak occurs. The demand parameters and dispersion are the same as the values for the piping component with the lowest median damage state demand. The unit of measure is one square foot. For floor flooding consequences, if the assumption is that the entire floor is flooded, the performance group quantity should be set to the area of entire floor. The user may assume only a part of floor is flooded by modifying the performance group quantities. The likelihood of floor flooding throughout a floor level is related to the presence of building maintenance personnel capable of rapidly shutting down sprinkler flow.

2.5.7.2 Raised Access Floors

This fragility classification (C302) is summarized in Table B-7 and includes raised access floors.

Two types of fragilities are provided: unanchored floors (C3027.001), including floors with adhesive attachment, and seismically-rated access floors with pedestals anchored and braced to the floor (C3027.002). Current seismic codes strongly encourage seismically-rated floors for buildings assigned to Seismic Design Categories D, E, or F. However, anchorage conditions vary considerably.

Peak floor acceleration (non-directional) is the demand parameter for raised access floors. Raised access floor systems are measured in units of 100 square feet, i.e., the floor area (in square feet) divided by 100.

2.5.8 Suspended Ceilings and Ceiling Lighting (C303)

This fragility classification (C303) is summarized in Table B-8 and comprises suspended lay-in ceilings and lighting systems.

Four types of suspended lay-in ceiling specifications are provided (C3032.001 through C3032.004), based on conformance to the prescriptive seismic detailing requirements of recent building codes. Types included are ceilings satisfying detailing requirements for: (1) Seismic Design Categories A and B; (2) Seismic Design Category C; (3) Seismic Design Categories D and E; and (4) Seismic Design Category F and where the importance factor $I_p = 1.5$ applies. Each of these ceiling fragility specifications is further subdivided by area of individual ceiling size. Ceiling size is a function of whether ceilings run continuously over partitions or are independent within each room on a floor. Four ceiling area sizes are provided: (1) less than or equal to 250 square feet; (2) 250 to 1000 square feet; (3) 1000 to 2500 square feet; and (4) greater than 2500 square feet. These area sizes reflect the increasingly more detailed prescriptive requirements contained in current codes corresponding to the ceiling area. Lighting fixtures are included in the lay-in ceiling specifications. For buildings of recent construction, if the ceiling type is not known, the specification associated with the building's current Seismic Design Category and appropriate ceiling area should be selected. For ceilings that predate the adoption of codes with seismic detailing criteria, fragilities associated with Seismic Design Category A should be selected.

Peak floor acceleration (non-directional) of the floor above is the demand parameter for ceiling systems. Volume 1, Appendix F provides guidance on total ceiling area per floor area, but does not address how to split the total ceiling area into different ceiling area subgroups based on room size. Users must exercise judgment in assigning these quantities. Each area subgroup uses a different quantity unit to measure this fragility. For areas less than or

equal to 250 square feet, the subgroup unit measure is 250 square feet. For ceiling areas between 250 square feet and 1000 square feet the performance group unit is 600 square feet. The unit for areas between 1000 square feet and 2500 square feet is 1800 square feet. The unit for areas greater than 2500 square feet is 2500 square feet.

Two fragility specifications are provided for suspended pendant lighting fixtures. One specification is provided for fixtures not seismically designed or braced (C3034.001) and another for seismically-rated fixtures with seismically designed restraints (C3034.002). Current seismic codes require seismically-rated lighting fixtures and pendant light fixtures for buildings in Seismic Design Categories D, E, or F, unless there is no potential for impact interaction. If the lighting fixture is free to swing during an earthquake and the components are detailed to accommodate the swing without impact, the user can consider the fixtures rugged and not include them in the assessment model.

Peak floor acceleration (non-directional) of the floor above is the demand parameter for suspended pendant lighting systems. Lighting systems are measured in individual units, i.e., “each.”

2.5.9 Elevators and Lifts (D101)

This fragility classification (D101) is summarized in Table B-9 and includes selections for hydraulic and traction elevators. Traction elevators are further divided into those with seismic provisions and those without. Seismic requirements were added to the design requirements for elevators in the 1975 California Building Code. These requirements substantially reduced the vulnerability of elevator systems and were adapted for other seismic zones in the ASTM A17.1, *Safety Code for Elevators and Escalators*, (ASME, 1981).

If the type of elevator is unknown, the user can assume that buildings with more than 5 stories will have traction elevators and buildings with 5 stories or less will have hydraulic elevators.

The number of elevators present in a building is a function of many factors but the primary determinants are the building’s gross square footage and occupancy type. Volume 1, Appendix F provides guidance on selecting the number of elevators based on floor area and occupancy. Performance groups for elevators should be defined only for the first floor.

Peak floor acceleration (non-directional) at the first floor is the demand parameter for elevators. Elevators are measured in individual units, i.e., “each.”

2.5.10 Domestic Water Distribution (D202)

This fragility classification (D202) is summarized in Table B-10 and includes cold and hot water piping. The specifications are divided into piping for cold and hot potable service, and heating hot water piping. The specifications are further divided into subgroups depending on the seismic design category and importance factor as follows: (1) Seismic Design Categories A and B; (2) Seismic Design Category C; (3) Seismic Design Categories D and E; and (4) Seismic Design Category D, E, or F where the importance factor, I_p , is 1.5. Further subdivision is made for water piping based on the pipe diameter and the use of threaded or welded steel connections. Separate specifications are provided for the piping itself and, in most cases, for anchorage and bracing supporting the piping. For these components, both specifications should be included in the performance model.

For recently constructed buildings, if the type of distribution system detailing is not known, the type appropriate to the building's Seismic Design Category and importance should be selected. For construction that predates the adoption of codes with seismic detailing for these systems, Seismic Design Category A should be assumed.

Peak floor acceleration (non-directional) in the floor above is the demand parameter for domestic water piping systems. Domestic water piping systems are measured in units of 1000 lineal feet, i.e., the total length of piping per floor (in lineal feet) divided by 1000.

As previously discussed in Section 2.5.7, it is possible to include a floor flooding fragility specification to account for flooding damage.

2.5.11 Sanitary Waste Piping (D203)

This fragility classification (D203) is summarized in Table B-11 and includes sanitary waste piping. These specifications are further divided into subgroups depending on seismic design category and importance factor similar to other piping types. Further subdivision is made for cast iron piping with flexible couplings and those with ball and spigot couplings. In most cases, separate specifications are provided for anchorage and bracing of ball and spigot couplings. Both specifications should be included in the performance model for these components.

Peak floor acceleration (non-directional) in the floor above is the demand parameter for these systems. Sanitary waste piping systems are measured in units of 1000 lineal feet, i.e., the total length of piping per floor (in lineal feet) divided by 1000.

As previously discussed in Section 2.5.7, it is possible to include a floor flooding fragility specification to account for flooding damage.

2.5.12 Chilled Water and Steam Piping (D205 and D206)

These fragility classifications (D205 and D206) are summarized in Table B-12 and Table B-13 and include chilled water and steam piping systems. These specifications are further divided into subgroups depending on seismic design category and importance factor similar to other piping types. Further subdivision is made for welded and threaded connections and for pipe diameters greater than 2.5 inches and less than 2.5 inches. Separate specifications are provided for both the piping itself and for anchorage and bracing supporting the piping. For these components, both specifications should be specified.

For recently constructed buildings, if the type of distribution system detailing is not known, the type appropriate to the building's Seismic Design Category and importance should be selected. For construction that predates the adoption of codes with seismic detailing for these systems, Seismic Design Category A should be assumed.

The demand parameter for these systems is peak floor acceleration (non-directional) in the floor above. These piping systems are measured in units of 1000 lineal feet, i.e., the total length of piping per floor (in lineal feet) divided by 1000.

As previously discussed in Section 2.5.7, it is possible to include a floor flooding fragility specification to account for flooding damage.

2.5.13 Chillers, Cooling Towers, and Compressors (D303)

This fragility classification (D303) is summarized in Table B-14 and includes chillers, cooling towers, and compressors. Each of these specifications is further subdivided by the installation characteristics including:

(1) unanchored and not isolated; (2) isolated and not restrained; and (3) hard anchored or isolated and restrained. Each of these subcategories is further subdivided by unit or by whether the unit services small or large medical systems (large and small are general terms subject to user judgment).

The final category used to differentiate among fragility specifications for these components is the dominant damage mode. Three possible damage modes are identified. These include:

- Anchorage failure: Equipment anchorage is relatively weak and fails well before the equipment is damaged.

- Internal damage: Equipment anchorage is relatively strong and the equipment suffers internal damage well before the anchorage fails.
- Simultaneously occurring anchorage failure and internal damage: Equipment anchorage fails and is accompanied by internal damage to the equipment.

Consequence functions are provided for each of these fragility specifications; however, users are required to define the median acceleration value associated with anchorage failure for each piece of equipment. With this calculated value, the **Fragility Specification Manager** utility can assist in determining the best selection for the dominant damage mode by comparing median floor accelerations for the anchorage and the equipment damage modes (PACT fragility selections for the equipment damage mode include median floor acceleration values and dispersion values). Users should:

- Select the anchorage failure damage mode if the median value of peak floor acceleration associated with anchorage failure is less than 30% of the value associated with internal damage to the equipment.
- Select the equipment internal damage mode if the median peak floor acceleration for internal equipment damage is less than 30% of the median value of acceleration associated with anchorage failure.
- Select the simultaneous anchorage failure and internal equipment damage mode for all other median acceleration ratios.

For equipment that is unanchored, only damage modes that include internal damage are provided in PACT. Users can define additional damage modes associated with failure of attached piping due to equipment sliding. Section 7.3 provides guidance on calculation of anchorage fragilities.

Peak floor acceleration (non-directional) is the demand parameter for these systems. Estimates of the size and number of equipment items likely to occur given the size and occupancy of the building under construction can be found in Volume 1, Appendix F and the *Normative Quantity Estimation Tool*. The capacity of an individual equipment item is expressed in terms of the gross square footage of building area it can serve. Depending on the total demand, the size and number of equipment units can be assigned. For equipment with capacity of less than 100 tons, the unit of measure is 75 tons. For equipment with capacity between 100 tons and 350 tons, the unit of measure is 250 tons. For equipment with capacity between 350 tons and 700 tons, the unit of measure is 500 tons. For equipment with capacity between 750 tons and 1,000 tons, the unit of measure is 850 tons. If the demand exceeds the capacity of any available unit (greater than 1,000 tons), two

items of equipment equal in size that provide the needed total capacity can be assigned. Most equipment identified in this category will be located on the first floor, basement or roof. Items should only be identified once for a given building. These systems are measured in individual units, i.e., “each.”

2.5.14 HVAC Distribution Systems (D304)

This fragility classification (D304) is summarized in Table B-15 and includes components of HVAC distribution systems including: in-line fans, ducting, drops and diffusers, variable air volume boxes, and fans.

In-line fan specifications are divided into subgroups that include units that are independently supported with vibration isolators (D3041.001) and those without vibration isolators (D3041.002). These systems are further divided depending on Seismic Design Category as follows: (1) Seismic Design Categories A and B; (2) Seismic Design Category C; (3) Seismic Design Categories D and E; and (4) Seismic Design Category D, E, or F.

Distribution ducting is divided into galvanized (D3041.011 and D3041.012) and stainless (D3041.021 and D3041.022) steel sheet metal. These specifications are further subdivided by size (less than or greater than 6 square feet in cross sectional area). Similar to in-line fans, ducting specifications are further subdivided by Seismic Design Category.

Drop and diffuser specifications are divided into categories of the installation location: in suspended ceilings (D3041.031) or without ceilings (D3041.032). These specifications are further subdivided by Seismic Design Category.

Variable air volume boxes (VAV) (D3041.041) are divided into two categories: Seismic Design Categories A or B and Seismic Design Category C or above.

HVAC fan specifications are divided into three categories: (1) unanchored and not isolated (D3041.101); (2) isolated but not restrained (D3041.102); (3) and hard anchored or isolated and restrained (D3041.103). These three categories are further subdivided by dominant damage mode (anchorage failure, internal damage, or simultaneous damage) in a manner similar to that done for the components in Section 2.5.13. In an analogous fashion, the user must determine the median value of peak floor acceleration that will produce anchorage or isolator failure and use that value to select the dominant damage mode most appropriate.

Peak floor acceleration (non-directional) in the floor above is the demand parameter for these systems. The fragilities are measured with the following units:

- In-line fans – number of 10 units
- HVAC ducting – number of 1,000 lineal feet units
- Drops or diffusers – number of 10 units
- VAV boxes – number of 10 units
- HVAC fans – number of items, “each”

2.5.15 Packaged Air Handling Units (D305)

This fragility classification (D305) is summarized in Table B-16 and includes packaged air handling units. These specifications are divided into categories for equipment that is unanchored and not isolated (D3052.011) and equipment that is hard anchored or isolated and restrained (D3052.013). Each of these categories is further subdivided by equipment size as follows:

- Equipment size < 5,000 cfm
- $5,000 \text{ cfm} \leq \text{Equipment size} < 10,000 \text{ cfm}$
- $10,000 \text{ cfm} \leq \text{Equipment size} < 25,000 \text{ cfm}$
- $25,000 \text{ cfm} \leq \text{Equipment size} < 40,000 \text{ cfm}$

The hard anchored or isolated and restrained category is further subdivided by the dominant damage mode. These selections include anchorage failure, internal damage, or the simultaneous occurrence of both. Note that for unanchored, not isolated equipment, only an internal damage mode is provided. Section 2.5.13 provides further information on estimating the median floor acceleration associated with anchorage failure and the use of that information to select the most appropriate damage mode.

Peak acceleration of the supporting floor (non-directional) is the demand parameter for these systems.

The size of an individual equipment item is expressed in terms of the gross square footage of building area it can serve. Depending on the total demand, the size and number of equipment units can be assigned. For equipment with a capacity smaller than 5,000 cfm, the unit of measure is 4,000 cfm. For equipment with a capacity between 5,000 cfm and 10,000 cfm, the unit of measure is 8,000 tons. For equipment with a capacity between 10,000 cfm and 25,000 cfm, the unit of measure is 20,000 cfm. For equipment with a capacity between 25,000 cfm and 40,000 cfm, the unit of measure is 30,000 cfm.

2.5.16 Control Panels (Table D306)

This fragility classification (D306) is summarized in Table B-17 and includes control panels. This category is further subdivided into unanchored and anchored panels. For unanchored systems, only one specification is provided (B3067.011a); however, for hard anchored panels, the user should select the most appropriate fragility specification based on a dominant damage mode that includes anchorage failure, internal damage, or the simultaneous occurrence of both. Section 2.5.13 provides further information on estimating the median floor acceleration associated with anchorage failure and the use of that information to select the most appropriate damage mode.

Peak acceleration of the supporting floor (non-directional) is the demand parameter for control panels. Control panels are measured in individual units, i.e., “each.”

2.5.17 Fire Protection (D401)

This fragility classification (D401) is summarized in Table B-18 and includes fire protection system components. Testing of connections indicate that vertical standpipes designed and installed in accordance with NFPA 13, *Standard for Installation of Sprinkler Systems*, (NFPA, 2007) have a median story drift ratio capacity exceeding 0.05 and are therefore considered seismically rugged.

Specifications for thin wall piping systems with older Victaulic type connections are subdivided by Seismic Design Category. The fragility specifications provided for the horizontal distribution system includes its bracing.

Fire sprinkler drop fragility specifications are subdivided into the following categories: (1) lay-in tile soft ceilings; (2) lay-in tile hard ceilings; and (3) no ceilings. Each of these groups is further divided based on Seismic Design Category. Seismic Design Categories A, B, or C imply no seismic requirements or lateral bracing of the ceiling while Seismic Design Category D, E, and F imply that lateral seismic bracing is provided with a stringent level of design and construction installation review.

Peak floor acceleration (non-directional) of the floor above is the demand parameter for these systems. Fire sprinkler piping systems are measured in units of 1,000 lineal feet per floor. Fire sprinkler drops are measured in units of 100.

2.5.18 Electrical Service and Distribution (D501)

This fragility classification (D501) is summarized in Table B-19 and includes the following building electrical components: motor control centers, primary service transformers, low voltage switchgear, and distribution panels.

Each of these fragility specifications are subdivided by the following considerations: (1) unanchored, not isolated; and (2) hard anchored or isolated and restrained.

For transformers, further subdivisions are made based on unit size as follows:

- 100 to 350 kVA – measured in units of 250 kVA
- 350 to 750 kVA – measured in units of 500 kVA
- 750 to 1,200 kVA – measured in units of 1000 kVA
- 1,200 to 2,000 kVA – measured in units of 1,500 kVA

For low voltage switchgear and distribution panels, the following subdivisions are used:

- 100 to 350 amp – measured in units of 225 amp
- 350 to 750 amp – measured in units of 400 amp
- 750 to 1,200 amp – measured in units of 800 amp
- 1,200 to 2,000 amp – measured in units of 1,600 amp

All of the fragility specifications are further divided by the dominant damage mode (anchorage failure, internal damage and simultaneous occurrence of both). Section 2.5.13 provides information on estimating the median floor acceleration associated with anchorage failure and the use of that information to select the most appropriate damage mode.

Peak floor acceleration (directional) of the supporting floor is the demand parameter for these systems. Motor control centers are measured in individual units, i.e., “each.” The size of transformers, switchgear, and distribution panels depend on the total demand. The units of measure for these systems are indicated above.

2.5.19 Other Electrical Systems (D509)

This fragility classification (D509) is summarized in Table B-20 and includes the following building electrical components not included in Section 2.5.18: battery racks, battery chargers, and diesel generators.

Fragility specifications for these items are subdivided into the following categories: (1) unanchored, not isolated; and (2) hard anchored or isolated and restrained.

Diesel generators include specifications for conditions where the equipment is isolated and not restrained, as well as the above conditions. Diesel generator fragility specifications are further subdivided by equipment size into the following groups:

- 100 to 350 kVA – measured in units of 250 kVA
- 350 to 750 kVA – measured in units of 500 kVA
- 750 to 1,200 kVA – measured in units of 1000 kVA
- 1,200 to 2,000 kVA – measured in units of 1,500 kVA

All fragility specifications in Table B-20 are further subdivided by dominant damage modes that include anchorage failure, internal equipment damage, or the simultaneous occurrence of both. Refer to Section 2.5.13 for further information on estimating the median floor acceleration associated with anchorage failure and the use of that information to select the most appropriate damage mode.

Peak floor acceleration (directional) of the supporting floor is the demand parameter for these systems. The units of measure for these diesel generators are indicated above.

2.5.20 Equipment and Furnishings (E20)

This fragility classification (E20) is summarized in Table B-21 and includes various building furnishings and contents, such as filing cabinets, bookcases, electronic equipment, fragile contents on shelves, and modular office workstations.

One fragility specification is provided for modular office work stations (E2022.001). The number of modular workstations per floor is user-specified, as is the replacement cost of each station.

Peak floor acceleration (non-directional) of the supporting floor is the demand parameter for these systems. Modular office work stations are measured in individual units, i.e., “each.”

Three types of specifications are provided for valuable fragile objects on shelves. These include: (1) unsecured objects on shelves with low friction surface (E2022.010); (2) secured objects on shelves (E2022.011), and (3) objects on cabinet shelves with latched doors (E2022.012). The quantity

and replacement cost of each group of objects of each type is specified by the user.

Peak floor acceleration (non-directional) of the supporting floor is the demand parameter for these systems. Fragile objects on shelves are measured in individual units, i.e., “each.”

Three categories are provided for electronic equipment (E2022.020): (1) home entertainment equipment on shelves; (2) electronic equipment mounted to walls (E2022.021); and (3) desktop electronic equipment including computers, monitors, and stereos. The third category is subdivided into equipment mounted on a slip-resistant surface (E2022.022) and equipment mounted on a smooth surface (E2022.023). The quantity and replacement cost of each item is specified by the user.

Peak floor acceleration (non-directional) of the supporting floor is the demand parameter for these systems. Electronic equipment is measured in individual units, i.e., “each.”

Two types of specifications are provided for bookcases (E2022.102a – E2022.106b). One is for unanchored bookcases and the other is for anchored bookcases. The specifications are further subdivided by the size of the bookcases. Fragility specifications are provided for five bookcase sizes.

Peak total floor velocity of the supporting floor is the demand parameter for unanchored bookcases. Fragility functions for these components were derived by calculation. Section 7.2.1 illustrates this calculation.

For anchored bookcases, the demand parameter is peak floor acceleration (non-directional) of the supporting floor. Fragility specifications are defined by the user and can be developed following the guidance provided in Chapter 7. Users also need to define the number of bookcases of each type on each floor and the replacement cost of the bookcase contents.

Two fragility specifications types are provided for filing cabinets (E2022.112a – E2022.125b). One type is for unanchored filing cabinets and the other is for anchored filing cabinets. The specifications are further subdivided depending on the size and orientation of the filing cabinets. Specifications are provided for two sizes each of vertical and lateral filing cabinets filing cabinets.

Peak total floor velocity of the supporting floor is the demand parameter for unanchored filing cabinets. Fragility specifications for these components have been derived by calculation. Section 7.2.1 illustrates this calculation.

For anchored filing cabinets, the demand parameter is peak floor acceleration (non-directional) of the supporting floor. Fragility specifications are user-defined and can be developed following the guidance in Chapter 7. The user needs to define the number of filing cabinets of each type on each floor. The performance group unit of input is the number of file cabinets of each type per floor.

2.5.21 Special Construction (F20)

This fragility classification (F20) is summarized in Table B-22 and includes industrial type storage racks designed and installed to satisfy the seismic design requirements enforced prior to 2007. Users must identify and input the number of racks and the replacement cost of the rack contents.

Peak floor acceleration (non-directional) of the floor supporting the rack is the demand parameter for storage racks. Storage racks are measured in units of 50 lineal feet, i.e., the total length of storage racks (in lineal feet) divided by 50.

2.5.22 Nonstructural Performance Groups

Nonstructural components are assembled into performance groups in a fashion similar to structural components. The *Normative Quantity Estimation Tool* provided in Volume 3 facilitates identification of performance group quantity information and distribution of common nonstructural building components.

To use this tool, users identify the floor area associated with each of 8 different occupancy types at each building level. The tool produces a floor-by-floor list of the performance group quantities of nonstructural components based on the floor area and occupancy type. The user should review values listed by the tool to confirm that the components and quantities selected are appropriate given the building size and quantity of discreet units required. Appendix D provides detailed instructions on the use of the *Normative Quantity Estimation Tool*.

Figure 2-9 shows the **Building Definition** table of the *Normative Quantity Estimation Tool* completed with number of floors and square foot for each occupancy present at each floor. Selection of occupancy categories for each floor will generate a listing of nonstructural fragility specifications and the quantities of components conforming to each specification as shown in Figure 2-10. The results from the tool should be reviewed for appropriateness with the building information available, such as seismic category and year of construction, and revised accordingly.

N floors	5
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BUILDING DEFINITION TABLE									
Floor Name	Floor #	Total Floor Area	Occupancy 1		Occupancy 2		Occupancy 3		SUM % AREA
		(sf)	Type	% Area	Type	% Area	Type	% Area	
Roof	5	23000	none	50%	none	50%	none	0%	100%
4th	4	23000	LABORATORY	50%	RETAIL	50%	none	0%	100%
3rd	3	23000	LABORATORY	50%	RETAIL	20%	WAREHOUSE	30%	100%
2nd	2	23000	LABORATORY	50%	OFFICE	20%	APARTMENT	30%	100%
1st	1	23000	LABORATORY	50%	OFFICE	20%	SCHOOLS	30%	100%

Component Summary Matrix														
OCCUPANCY				Fragility Number	Fragility Name	Assumed Quantity per component within PACT	Quantity		Correlated Fragility?	Actual Quantity		PACT Basic Unit	Fragility Quantity Ratio (LogNormal Distribution)	
Type	Occupancy #	Floor Name	Component Area (sq ft)				Directional	Non Directional		Value	Unit			
LABORATORY	1	1st	11500	B002Z.001	B002.001	Curtain Walls - Generic Midrise Stick-Built Cur	30 SF	57.50	--	NO	1775.0	SF	OK	0.8
LABORATORY	1	1st	11500	B001.011	B001.011	Concrete tilt roof, tiles secured and compl	100 SF	5.78	--	NO	2017.5	SF	OK	0.2
LABORATORY	1	1st	11500	C011.001A	C011.001A	Wall Partition, Type: gypsum with metal stud	100 LF	--	--	NO	972.5	LF	OK	0.8
LABORATORY	1	1st	11500	C011.001A	C011.001A	Wall Partition, Type: Gypsum + Wallpaper, F	100 LF	0.58	--	NO	98.0	LF	OK	0.8
LABORATORY	1	1st	11500	C0302.001A	C0302.001A	Suspended Ceiling, SDC A/B, Area (A): A < 250	250 SF	--	39.10	NO	977.5	SF	OK	0.8
LABORATORY	1	1st	11500	D022.112A	D022.112A	Vertical Filing Cabinet, 2 drawer, unanchored	1 EA	--	3.45	NO	15	EA	OK	0.8
LABORATORY	1	1st	11500	D022.102A	D022.102A	Bookcase, 2 shelves, unanchored laterally	1 EA	--	0.45	NO	34.5	EA	OK	0.2
LABORATORY	1	1st	11500	D022.011A	D022.011A	Cold Water Piping (dia > 2.5 inches), SDC A or	1000 LF	--	0.23	NO	230.0	LF	OK	0.2
LABORATORY	1	1st	11500	D022.011A	D022.011A	Hot Water Piping - Small Diameter Welded St	1000 LF	--	1.38	NO	1380.0	LF	OK	0.3
LABORATORY	1	1st	11500	D022.021A	D022.021A	Hot Water Piping - Large Diameter Welded St	1000 LF	--	0.46	NO	460.0	LF	OK	0.4
LABORATORY	1	1st	11500	D031.011B	D031.011B	Sanitary Waste Piping - Cast iron w/flexible	100 LF	--	0.92	NO	920.0	LF	OK	0.3
LABORATORY	1	1st	11500	D031.011B	D031.011B	HVAC Galvanized Sheet Metal Ducting - 4 in	100 LF	--	0.48	NO	375.0	LF	OK	0.2
LABORATORY	1	1st	11500	D041.011A	D041.011A	HVAC Galvanized Sheet Metal Ducting less th	1000 LF	--	1.15	NO	1150.0	LF	OK	0.2
LABORATORY	1	1st	11500	D041.011A	D041.011A	HVAC Drops / Diffusers in suspended ceiling	10 EA	--	18.40	NO	184.0	EA	OK	0.2
LABORATORY	1	1st	11500	D041.041A	D041.041A	Variable Air Volume (VAV) box with in-line c	10 EA	--	2.30	NO	23.0	EA	OK	0.2
LABORATORY	1	1st	11500	D041.041A	D041.041A	Variable Air Volume (VAV) box with in-line c	10 EA	--	0.35	NO	3.5	EA	OK	0.7
LABORATORY	1	1st	11500	D061.011A	D061.011A	Steam Piping - Small Diameter Welded Steel	1000 LF	--	0.12	NO	115.0	LF	OK	0.2
LABORATORY	1	1st	11500	D061.021A	D061.021A	Steam Piping - Large Diameter Welded Steel	1000 LF	--	0.23	NO	230.0	LF	OK	0.2
LABORATORY	1	1st	11500	D022.011A	D022.011A	Hot Water Piping - Small Diameter Welded St	1000 LF	--	0.92	NO	920.0	LF	OK	0.2
LABORATORY	1	1st	11500	D022.021A	D022.021A	Hot Water Piping - Large Diameter Welded St	1000 LF	--	0.35	NO	345.0	LF	OK	0.2
LABORATORY	1	1st	11500	C0303.001	C0303.001	Recessed lighting in suspended ceiling - no in	1 EA	--	172.50	NO	172.5	EA	OK	0.2
LABORATORY	1	1st	11500	C0304.001	C0304.001	Independent Pendant Lighting - non seismic	1 EA	--	172.50	NO	172.5	EA	OK	0.2
LABORATORY	1	1st	11500	D0411.021A	D0411.021A	Fire Sprinkler Water Piping - Horizontal Man	1000 LF	--	2.30	NO	2300.0	LF	OK	0.1

The *Normative Quantity Estimation Tool* assigns a measure of variability to the median quantities reported. For distributed systems, such as piping, ducting, and ceilings, the quantity variability can take a normal or lognormal form. Dispersion and coefficient of variation values are provided for these components and can be assigned to the performance group quantity input into PACT. For discrete items, such as boilers and cooling towers, dispersion values are not provided. Users should adjust the whole integer quantity of these items directly. For distributed systems, such as piping and partitions, the workbook will typically provide quantities in decimal fractions of a unit. If the fragility of such components is assumed to have correlated fragilities, these decimal fractions can be entered into PACT directly. However, if the fragility functions of such components are considered uncorrelated, only integer values should be entered.

2.6 Collapse Fragility Analysis

Once the building performance model has been developed and input into PACT, a building collapse fragility function must be developed to permit assessment of casualties. The collapse fragility function expresses the probability of building collapse, in one or modes, as a function ground motion intensity.

Collapse fragility functions include definition of the median spectral response acceleration at the building's effective fundamental period $\hat{S}_a(T)$ and a dispersion β associated with collapse, the possible collapse modes (expressed as a percentage of each floor area impacted by collapse and the number of stories involved in the collapse), the probability of each collapse mode given that collapse occurs, and the probability of incurring serious injuries and fatalities in an area of collapse.

The following sections discuss three general approaches to developing collapse fragility functions, as described in Volume 1, Chapter 6.

2.6.1 Nonlinear Response History Analysis

This approach uses results from a large number of nonlinear response history analyses to identify the probability of building collapse at different seismic intensities. A lognormal distribution is fit to the collapse cases generated for each intensity. The *Collapse Fragility Tool* provided in Volume 3 is an Excel workbook application that fits a lognormal distribution to collapse statistics obtained from a series of nonlinear dynamic analyses at different ground motion intensity levels.

The validity of the fragility parameters derived from this approach is dependent upon the number and quality of analyses performed and the number of intensities evaluated.

2.6.2 Simplified Nonlinear Analysis

Development of collapse fragility parameters using nonlinear static analysis is best suited to low-rise buildings of regular configuration. The approach relies upon archetypical incremental dynamic analysis (IDA) curves developed from nonlinear single-degree-of-freedom models of varying properties that are accessible through the *Static Pushover 2 Incremental Dynamic Analysis (SP2OIDA) Tool* provided in Volume 3. This tool is based on Vamvatsikos and Cornell (2006). The process for constructing a collapse fragility function using this approach consists of the following steps:

Step 1. Develop an appropriate mathematical model of the building for nonlinear static analyses. The procedures and recommendations contained in ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings*, (ASCE, 2007) for the nonlinear static procedure (NSP) can be used to generate the mathematical model.

Step 2. Following the procedures of ASCE/SEI 41-06, perform nonlinear static analyses to identify the sequence of simulated and non-simulated

failures for each principal building direction. Extend the analyses to a deformation such that collapse is judged to occur.

Step 3. Construct a force-displacement (pushover) relationship in each principal direction of building response.

Step 4. Approximate the force-displacement relationship(s) into idealized piecewise linear representations that include the reference control points for use as input parameters for the *Static Pushover 2 Incremental Dynamic Analysis* (SPO2IDA) tool provided in Volume 3. The tool utilizes the idealized pushover curve representation illustrated in Figure 2-11. Four control points define the general characteristics of the piece-wise linear curve.



Figure 2-11 SPO2IDA idealized pushover curve for hypothetical structure.

The branch of the curve from the ordinate to point 1 is defined as the elastic segment. Point 1 is defined as the yield point. The curve segment from point 1 to point 2 is termed the hardening segment, where point 2 is defined as the point of peak strength. The segment from point 2 to point 3 is termed the softening branch, where point 3 represents the onset of residual strength response. The segment from point 3 to point 4 represents the residual strength plateau and terminates abruptly at point 4. Point 4 represents the ultimate deformation at collapse. Definition of the control points can be such that slopes of the various branches are substantially different than those shown in the figure, and control points can coincide to eliminate branches, if appropriate.

After definition of the control points, the tool will require the following additional input information:

- Building weight,
- Building height, and

- Fundamental period.

Step 5. Execute SPO2IDA and extract the median collapse capacity. The median collapse estimate for S_a is found on the **IDA results** Tab as the last row entry in the S_a column.

Step 6. Define the collapse fragility function using the median collapse capacity from SPO2IDA and an assigned dispersion of 0.6.

The example below illustrates this procedure for a two-story, reinforced masonry shear wall building with a reinforced concrete slab supported by perimeter masonry walls and a system of reinforced concrete gravity frames, as shown in Figure 2-12 and Figure 2-13. The building has been designed to resist seismic forces prescribed by ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010) including minimum base shear and story drift limitations. Basic design characteristics are as follows:

$$R = 5, T_x = T_y = 0.13s, C_v = 0.20$$

For $S_{DS} = 1.0g$, $W = 1133$ kips (per wall) and $V = 227$ kips (per wall)

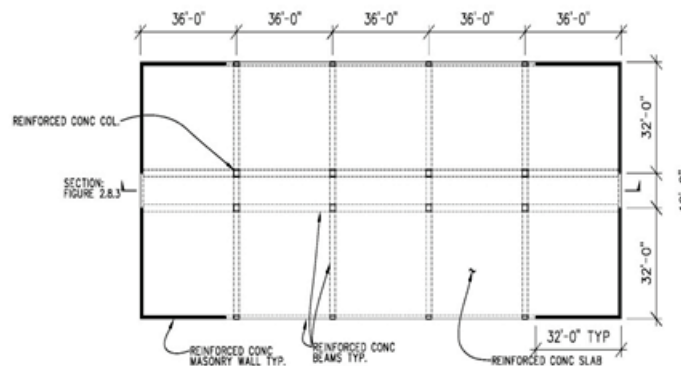


Figure 2-12 Plan of example structure.

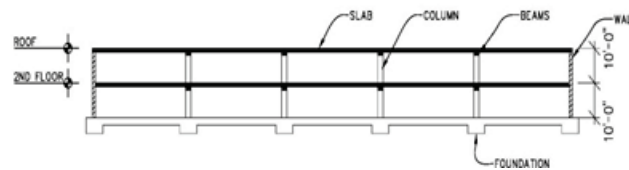


Figure 2-13 Section of example structure.

Step 1. A mathematical model is constructed in general accordance with the nonlinear static analysis provisions of ASCE/SEI 41-06.

Step 2. Perform nonlinear static analyses (for each principal direction) of the building to develop a force-displacement characterization of response (pushover curve). For the example structure, the response is identical about each principal building direction.

Step 3. Construct the force-displacement relationships for each principal building direction and plot the data. Figure 2-14 illustrates the results of a pushover analysis of the subject structure.

For this example, collapse is a non-simulated rupture of flexural wall reinforcement. Reinforcement rupture is judged to occur at an extensional strain of 0.05. Collapse is defined at a deformation level at which 30% of the cross section reinforcement rupture.

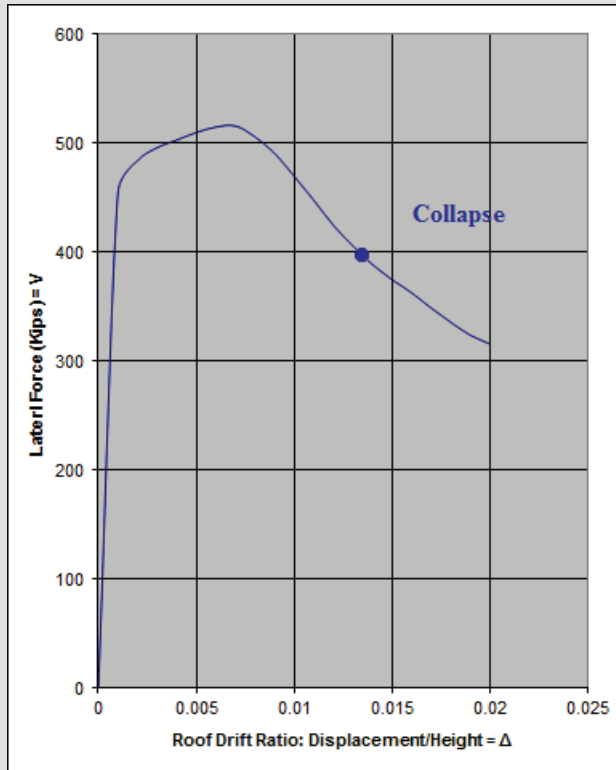


Figure 2-14 Pushover curve for 2-story reinforced masonry building.

The pushover curve data is input into SPO2IDA using the **SPO** tab. Note that drift index is used (Column C) to define deformation data. See Figure 2-15 for data input. Other data needed to complete the input include:

- Building weight: 1,133 kips
- Building height: 20 feet
- Fundamental period: 0.26s

Step 4. Identify the control points used in SPO2IDA to generate an idealized pushover curve by entering base shear and roof drift data into cells L30 through L33 and M30 through M33. These control points should be selected to best match the actual pushover curve. Superposition of the original curve and the control points is illustrated in the graphical window. See Figure 2-15.

Step 5. Execute SPO2IDA and extract the median collapse capacity. See Figure 2-16. The results are found on the **IDA results** tab, as shown in Figure 2-16. The last row of the S_a column provides the median estimate of spectral acceleration at collapse.

Step 6. Construct the fragility using the median estimate of $\hat{S}_a(\bar{T}) = 1.8g$ and an assigned dispersion of 0.6. See Figure 2-17.

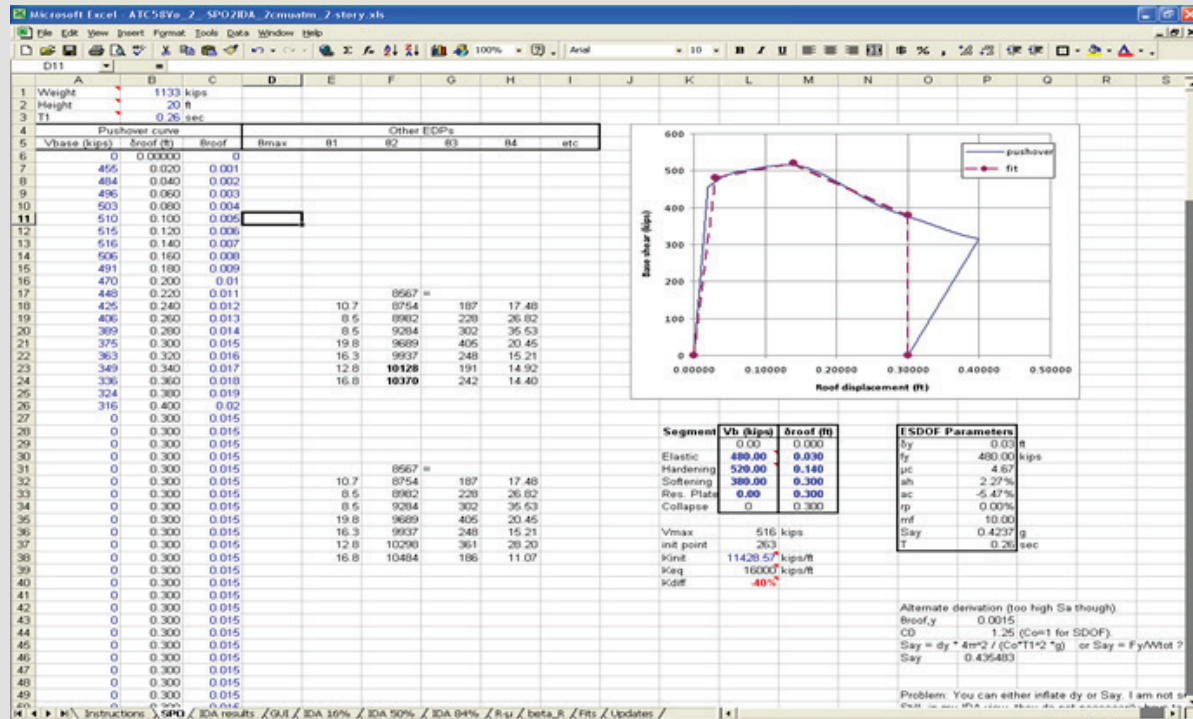


Figure 2-15 SPO2IDA Input.

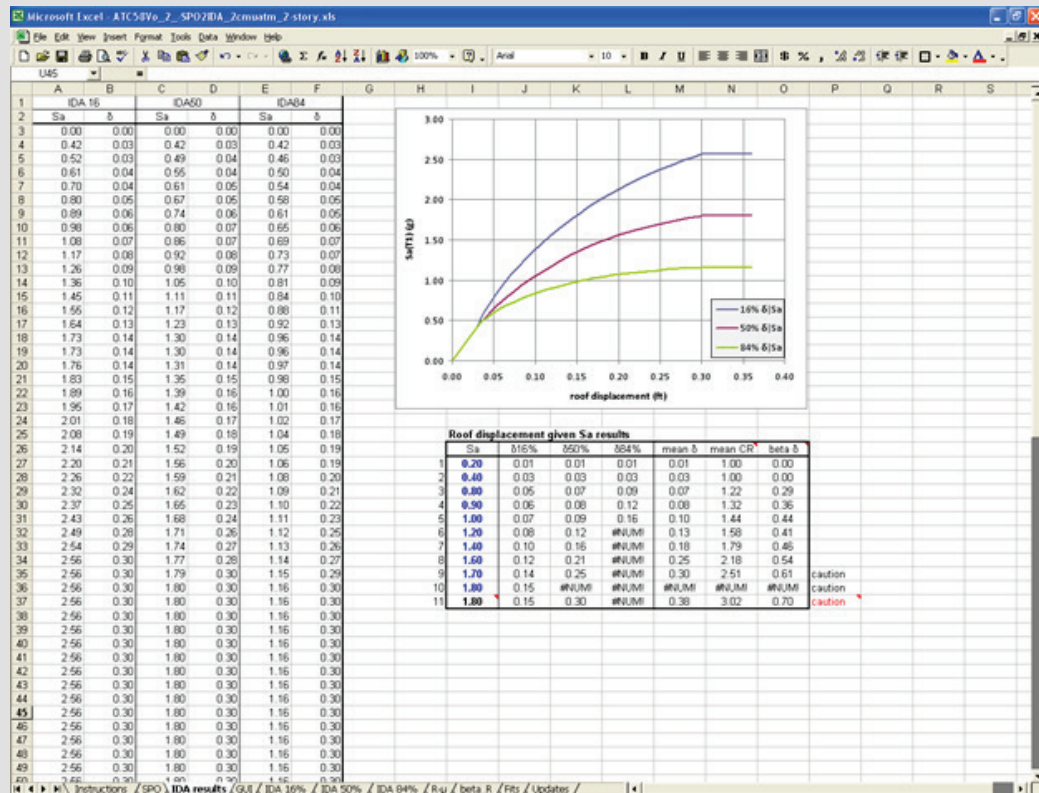


Figure 2-16 SPO2IDA Output.

2.6.3 Judgment-Based Approach

This approach to collapse fragility function development is best suited for buildings that conform to the requirements of recent building codes. The judgment-based process consists of the following steps:

Step 1. Estimate the highest value of base shear, V , the structure can resist in each principal direction while just in full conformance with the provisions of ASCE/SEI 7-10 and its reference standards.

Step 2. Calculate the effective value of the design spectral acceleration at the structure's fundamental period, S_{aD} , at which the structure satisfies all applicable ASCE/SEI 7 criteria as follows:

$$S_{aD} = \frac{V}{W} R$$

where V is the base shear determined in Step 1; W is the structure's seismic weight and R is the response modification coefficient of the structure as defined in ASCE/SEI 7.

Step 3. Calculate the inferred median collapse capacity, $\hat{S}_a(T)$ at the building's fundamental period, T , using the formula below:

$$\hat{S}_a(T) = 4S_{aD}$$

Step 4. Convert the computed median collapse capacity at the building's fundamental period, T , to that at \bar{T} .

$$\hat{S}_a(\bar{T}) = \frac{T}{\bar{T}} S_a(T), \text{ where } T \geq 0.6 \text{ seconds}$$

$$\hat{S}_a(\bar{T}) = S_a(T), \text{ where } T < 0.6 \text{ seconds}$$

Step 5. Construct the collapse fragility curve using the median values derived in Step 4 with a dispersion of 0.6 assigned for regular, well configured construction and 0.7 or higher for irregular structures or those with configurations/attributes suggesting poorer seismic performance than structures of a regular nature.

The example below demonstrates the derivation of a judgment-based collapse fragility using the sample structure previously described.

As previously described, the structure is a 2-story reinforced masonry shear wall building designed for ASCE/SEI 7 seismic forces with the following design characteristics:

$$R=5, T_x = T_y = 0.13\text{s}, C_v = 0.20, S_{DS} = 1.0\text{g}, W=1133 \text{ kips}$$

Second Edition Update

This example has been updated in accordance with the updated definition of inferred median collapse capacity.

Step 1. Define the highest value of base shear the structure can resist while in full conformance with ASCE/SEI 7-10:

$$V = C_v W = 0.20(1133) = 227 \text{ kips}$$

Step 2. Calculate the effective value of the design spectral acceleration at the structure's fundamental period

$$S_{aD} = \frac{V}{W} R = \frac{227}{1133} (5) = 1.00 \text{ g}$$

Step 3. Calculate $\hat{S}_a(T)$ for $T = 0.13$ seconds

$$\hat{S}_a(T) = 4C_4 S_{aD}$$

$$C_4 = \frac{\sqrt{2R-1}}{R} = \frac{\sqrt{(2)(5)-1}}{5} = 2.40 \text{ g}$$

Step 4. Convert $\hat{S}_a(T)$ to $\hat{S}_a(\bar{T})$

For $0.6s \leq T$: $\hat{S}_a(\bar{T}) = \hat{S}_a(T)$

Yielding $\hat{S}_a(\bar{T}) = 2.40 \text{ g}$

Step 5. Assign a dispersion of 0.6 in recognition of the regular configuration of the building.

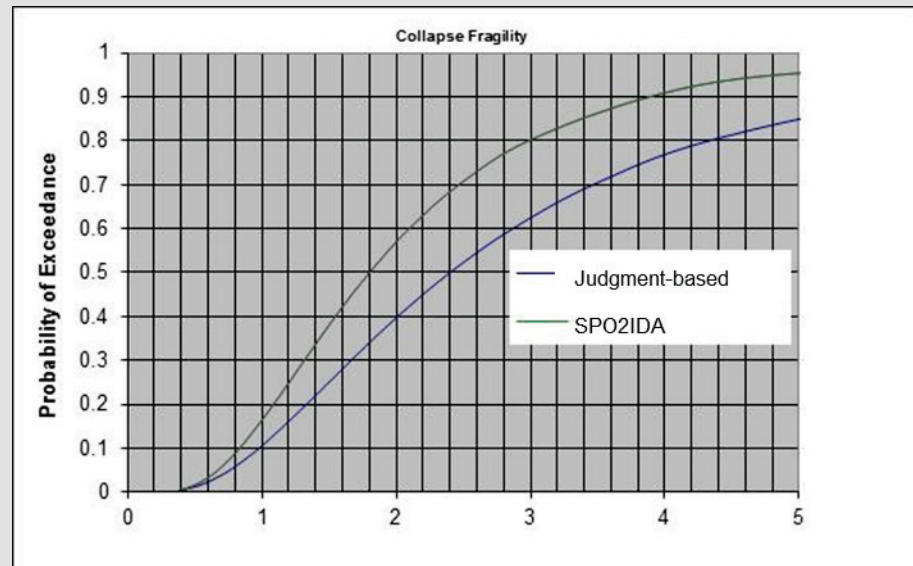


Figure 2-17 Comparison of collapse fragility functions obtained with two different approaches: SPO2IDA and Judgment.

Figure 2-17 shows the collapse fragility functions derived from both the nonlinear static procedure using SPO2IDA and the judgment-based

procedure. As can be seen there is significant difference between the two functions. This difference can be attributed to a combination of the inaccuracies inherent in the present basis for code-specified response modification factors and the assumptions inherent in the nonlinear static procedure as to what constitutes collapse.

2.6.4 Collapse Modes and PACT Input

When buildings collapse, they can collapse in different modes. For example, multi-story structures can experience single-story collapse in any of the stories or the entire structure can collapse. To quantify the impact of partial or total building collapse, it is necessary to define the various collapse modes that can occur, and to identify the fraction of building floor area at each level that experiences collapse in each mode. For each realization in which collapse is predicted, PACT utilizes a matrix of collapse ratios to determine the extent of building area involved in the collapse, and the number of occupants at risk. The following steps can be used to define the collapse ratios for input to PACT:

Step 1. Identify the likely collapse modes based on the results of analysis and judgment. This includes identification of building portions that are prone to collapse. Figure 2-18 illustrates some representative collapse modes for a 2-story building.

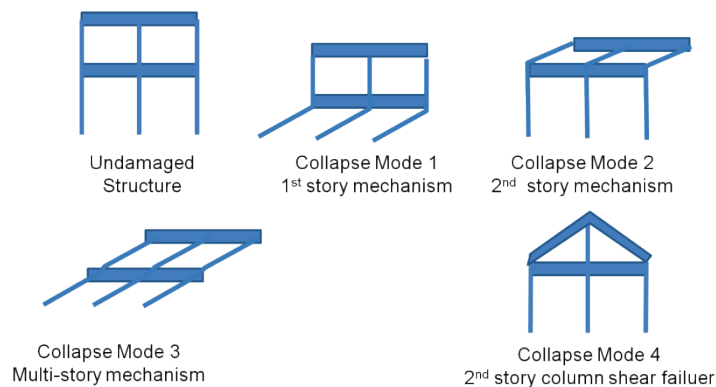


Figure 2-18 Illustration of multiple collapse modes.

Step 2. For each potential mode of collapse, estimate a probability of occurrence assuming the collapse modes are mutually exclusive, that is, the probabilities of all modes must sum to a value of 1.0.

Step 3. For each collapse mode, identify the fractional area of each floor that will either collapse directly or will be covered by debris from the collapsing floor above. In the illustration of Figure 2-18, collapse mode 1 is a 1st story collapse, in which 100% of the first story floor area is compressed, but none of the second. Collapse mode 2 is a 2nd story collapse in which 100% of the

second story floor area is compressed but none of the 1st. Collapse mode 3 is a total collapse in which 100% of the areas of both floors is involved in the collapse. Collapse mode 4 is a partial collapse of the 2nd story, in which perhaps 40% of the 2nd floor area is subject to space compression.

When collapse occurs, PACT requires definition of the **Mean Fatality Rate** (and associated COV) and the **Mean Injury Rate** (and associated COV). The **Mean Fatality Rate** is the fraction of occupants inhabiting the impacted collapse area who are fatally injured by the collapse. Users should select values based on judgment considering the types of debris likely to be generated given the construction type and its lethality. A similar judgment is required for **Mean Injury Rate**. These two values should sum to a value of 1.0.

2.7 Residual Drift Fragility

The final building characteristic necessary for PACT input is a measure of the building's global reparability. This measure of reparability is expressed on the **Residual Drift** tab (See Figure 2-19).

This fragility function expresses the probability that for a given value of residual story drift ratio, the building will be repaired or not. As the value of residual drift becomes larger, it will become impractical to repair the damaged building components while ignoring the permanent building distortion. Building recentering to correct residual drift is not generally practical and therefore large residual drifts can result in the building damage state being irreparable.

PACT provides an assumed fragility function for residual drift ratio that uses a median value for irreparability of 1% residual story drift and a dispersion of 0.3, as shown in Figure 2-19. Volume 1 Appendix C provides discussion of residual drift.

Construction of the building performance model is complete with the definition of the **Residual Drift Median** and **Residual Drift Dispersion**.

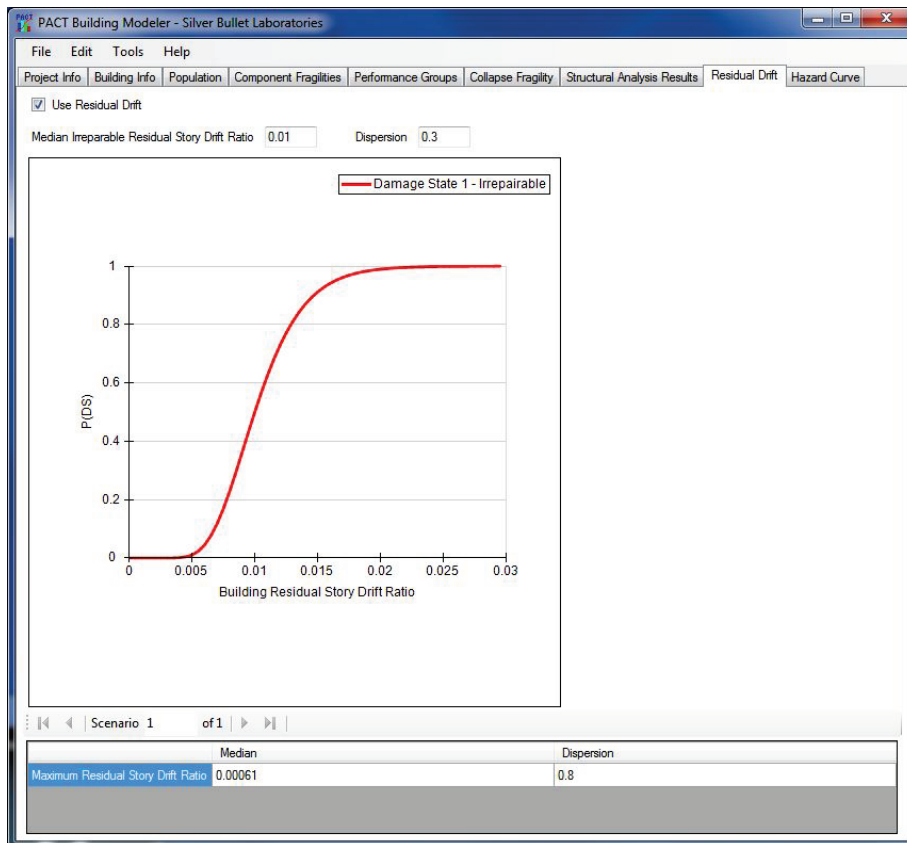


Figure 2-19 PACT Residual Drift tab.

Chapter 3

Building Analytical Model and Performance Assessments

3.1 Introduction

This chapter presents procedures necessary to evaluate a building's probable performance for different assessment types with different analysis methods, and illustrates data entry into the *Performance Assessment Calculation Tool* (PACT) provided in Volume 3. Each of the three assessment types (intensity-based, time-based, and scenario-based) can be executed using either the simplified analysis procedure or the more detailed nonlinear response history analysis method. Figure 3-1 illustrates the steps common to all assessment types and analysis methods. Chapter 2 provided guidance for assembling the building performance model.

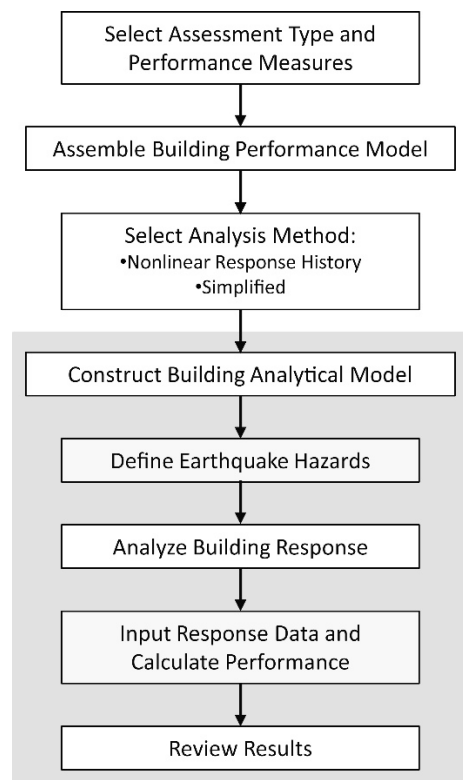


Figure 3-1 Performance assessment procedure showing steps covered in this chapter in shaded box.

3.2 Building Analytical Model

An analytical model of the building is required for both the nonlinear response history and simplified analysis approaches. Volume 1, Chapter 5 provides guidance on building and component modeling. This section summarizes some basic modeling considerations that support execution of the analyses presented in later sections.

3.2.1 Nonlinear Response History Analysis

For use in nonlinear response history analysis, a building should be modeled as a three-dimensional assembly of components including foundations and soils, as appropriate. Two-dimensional models are not recommended, and if used, an individual model is required for each of the building's primary response directions, with ground motion pairs applied, such that one component is used in the model representing direction 1 and the second in the model representing direction 2.

Components should be modeled over their full range of expected deformation response using hysteretic properties based upon test data. Where test data are lacking, idealized backbone curves, as described in ASCE/SEI 41-13, *Seismic Evaluation and Retrofit of Existing Buildings*, (ASCE, 2014) can be used. The model should explicitly include component strength and stiffness degradation. Volume 1, Chapter 5 provides a more detailed discussion of component degradation modeling.

Median values of component properties, such as yield deformation, yield strength, and capping strength, should be used. Mean or expected values may be substituted where insufficient information is available to accurately capture a median value.

Models should include dead and expected live loads acting throughout the building. Live loads can be taken as 25% of the code specified design live load without further reduction for influence area.

Equivalent viscous damping should generally be limited to 1% to 5% of critical damping to account for the effects of nonstructural components and soil-structure interaction not explicitly included in the analytical model. The majority of energy dissipated during building response should be generated by the hysteric behavior of the modeled components.

The response of relatively stiff buildings on relatively soft soils and buildings with a basement that extends more than one story beneath grade can be significantly affected by soil-structure interaction. Soil-structure interaction and foundation embedment effects can be modeled explicitly or accounted

for using approximate methods. Volume 1, Appendix B provides guidance and discussion of these topics.

Models should be structured to return values of the demand parameters associated with the fragility specifications used to assess performance. For example, fragility functions for eccentrically braced frame systems use link beam rotation as the demand parameter. Models of eccentrically braced frame structures should be configured to provide this demand value. Values for story drift ratio should reflect only the racking drift ratio component of total story drift ratio and not the contribution attributable to rotation from lower floors of the building. For taller structures and those that include wall systems, one means of obtaining this drift ratio is to include elastic cross brace members with low stiffness whose elongation will not be influenced by the rotational effects of the components below. The elongation (or shortening of these members) can be used to calculate shear drift ratio.

To the extent possible, the model should explicitly include the range of component deformation to failure. Where this cannot be done, users should estimate the deformation limits at which failure of these components is likely to occur. Users should carefully review analysis results and adjust them to account for these non-simulated component failures.

3.2.2 *Simplified Analysis*

Simplified analysis uses a linear elastic structural model and an estimate of the building's lateral yield strength to estimate response, and determine estimated median values of peak story drift ratios, residual drift ratios, peak floor acceleration, and peak floor velocity. Building response is assumed to be uncoupled along the principal horizontal building axes. Separate analyses are performed for each response direction. Simplified analysis assumes the following:

- Building response along each horizontal axis is uncoupled.
- The building is regular in plan and elevation (i.e., there are no substantial discontinuities in lateral strength and stiffness).
- Story drift ratios do not exceed four times the corresponding yield drift ratio, so that assumptions of elastic-plastic (bilinear) response at the component level are not substantially compromised by excessive degradation in strength and stiffness.
- Story drift ratios are less than 4%, beyond which P- Δ effects may become important.

- The building is less than 15 stories in height, minimizing the potential for significant higher mode effects.

If the building being assessed does not conform to these assumptions, the simplified procedure may produce unreliable results.

Mathematical models should use best-estimate distributions of mass and lateral stiffness. All elements that contribute significantly to the building's lateral strength or stiffness should be included in the model, whether or not these elements are considered to be structural or nonstructural, or even part of the seismic-force-resisting system. Strength and stiffness modeling guidance provided in ASCE/SEI 41-13 for typical components can be used in simplified analysis.

3.2.3 Demand Directionality

Users must enter peak floor acceleration, velocity, and story drift ratio values into PACT in each direction. PACT computes non-directional drift ratio, velocity and acceleration as 1.2 times the maximum of the two values obtained at each floor along the two horizontal axes.

3.3 Intensity-Based Assessment

Intensity-based assessments provide expression of a building's probable performance for a specified intensity of shaking at the building site. The specified shaking intensity is represented by a user-defined 5% damped elastic acceleration response spectrum.

3.3.1 Nonlinear Response History Analysis

3.3.1.1 Define Earthquake Hazards

Intensity is characterized by pairs of ground motion records that are selected and scaled for compatibility with a 5% damped elastic acceleration response representing the shaking intensity. The spectrum is assumed to represent the geometric mean of two orthogonal horizontal components of ground motion. The guidance for ground motion selection and scaling provided in Volume 1 is summarized below and presented with the following steps:

Step 1. Determine the building's fundamental translational periods in two orthogonal directions (T_l^X and T_l^Y).

Step 2. Determine the effective first mode period \bar{T} as the average of T_l^X and T_l^Y , if response in the two directions are uncoupled and as the larger of T_l^X or T_l^Y , if response is coupled.

Step 3. Using the target response spectrum, extract the $S_a(\bar{T})$ value.

Step 4. Select a candidate suite of recorded ground motion pairs having geomean spectral shape similar to the target spectrum. Recorded ground motions are available from a number of sources including: <https://ngawest2.berkeley.edu/> and www.cosmos-eq.org (last accessed March 15, 2018).

Step 5. Construct the geomean response spectrum for each ground motion pair using Volume 1, Equation 4-1:

$$S_{gm}(T) = \sqrt{S_x(T) \times S_y(T)}$$

where $S_x(T)$ and $S_y(T)$ are orthogonal components of spectral response acceleration at period T .

Step 6. Determine the periods T_{min} and T_{max} over which the suite of ground motion pairs are scaled to be consistent with the target spectrum. T_{max} is obtained from the equation:

$$T_{max} = 2\bar{T}$$

Period T_{min} should typically be taken as the smaller of $0.2 T_l^X$ or $0.2 T_l^Y$. If substantial damage can occur due to response in modes having periods smaller than T_{min} , e.g., in high rise buildings where multiple higher modes may contribute significantly to the acceleration and drift response, select T_{min} sufficiently small to capture these important response modes.

Step 7. Compare each pair's geomean spectral shape with that of the target spectrum over the range T_{min} to T_{max} . Select ground motion pairs with geomean spectra that are similar in shape to the target response spectrum within that range. Discard ground motion pairs that do not fit the shape of the target spectrum adequately.

Step 8. Amplitude-scale both components of each ground motion pair by the ratio of $S_a(\bar{T})$ obtained from the target spectrum to that of the geomean spectrum for the pair.

Figure 3-2 shows scaled spectra for a suite of 5 motions selected for intensity-based assessment of a structure with $\bar{T} = 0.5$ seconds. The ground motion pairs were selected with geomean spectral shape similar to the target (a code-spectrum with $S_a(0.2) = 1.0g$ and $S_a(1.0) = 0.6g$) over the period range 0.1 second to 1.0 second. For the selected suite of motions and scale factors, the average value of S_a for the suite is 98% of the target value and over the range of periods (0.1 second to 1 second) the average ordinate of the geomean spectrum has an error of 1.5%. Note that at any period, some records are substantially higher than the target spectrum and some, less.

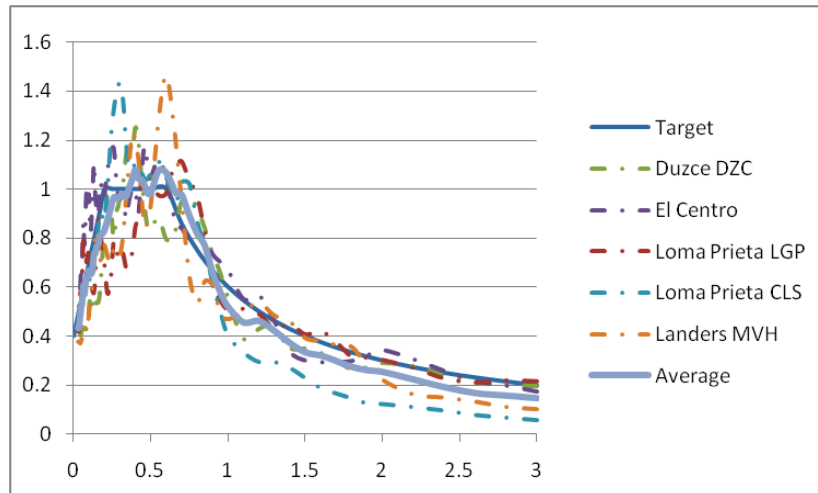


Figure 3-2 Example spectra for scaled suite of 5 motions.

The number, n , of ground motion pairs necessary to obtain valid estimates of median response depends on the extent that the geomean spectral shape of the scaled motions matches that of the target spectrum in the period range T_{min} to T_{max} . Limited study suggests that when a good match between the spectral shape of the selected motions and the target spectrum is obtained, use of relatively few records can provide a reasonable prediction of median response along the building height. When ground motions are selected without consideration of spectral shape, analyses using eleven pairs of motions, scaled in accordance with the recommendations of Volume 1, Chapter 4 can provide a reasonable estimate ($\pm 20\%$) of median response with 75% confidence (Huang et al., 2008). Use of fewer than 7 pairs is not recommended regardless of the goodness of fit of the spectra to that of the target because of the extremely poor predictions of record-to-record variability obtained from small suites of ground motions.

3.3.1.2 Analyze Building Response

Response calculations are performed with the n ground motion pairs described in Section 3.3.1.1. Peak transient drift ratios, peak floor accelerations, peak total floor velocities, and residual drift ratios are obtained as follows:

Step 1. Execute an analysis of the structure for each of the ground motion pairs.

Step 2. Extract the peak transient drift ratio, peak total floor velocity, and peak total floor accelerations from the analysis for each principal building direction and at each floor and story.

Note that many structural analysis software packages do not provide peak total acceleration or peak total velocity output. Peak total floor acceleration is the acceleration of a floor relative to a fixed point in space, rather than relative to the ground. Peak total floor velocity is the velocity of a floor relative to a fixed point in space, rather than relative to the ground. If the software used to perform the analysis does not provide total acceleration or total velocity as an output quantity, these must be derived from the output that is available. At each analysis time step, peak total velocity can be derived as the first derivative of the total displacement, taken as the difference between two subsequent total displacement values divided by the time step. Note that the total displacement must be determined as the difference between the story floor displacement and the ground displacement, on a time step by time step basis. Peak total acceleration can be derived in a similar manner as the second derivative of total floor displacement or first derivative of velocity.

Step 3. Estimate residual drift ratio from the peak transient drift ratios according to Volume 1, Equation 5-25:

$$\begin{aligned}\Delta_r &= 0 && \text{for } \Delta \leq \Delta_y \\ \Delta_r &= 0.3(\Delta - \Delta_y) && \text{for } \Delta_y < \Delta < 4\Delta_y \\ \Delta_r &= (\Delta - 3\Delta_y) && \text{for } \Delta \geq 4\Delta_y\end{aligned}$$

where:

Δ = values of median story drift ratio determined in Step 2

Δ_y = median story drift ratio calculated at yield

At values of ground shaking intensity $S_a(\bar{T})$ that approach the structure's median collapse capacity, it is likely that one or more of the n sets of ground motion pairs will result in prediction of structural collapse, evidenced by solution instability, predicted story drift ratio that exceeds the structural model's range of analytical validity, or predicted demands that suggest the onset of one or more non-simulated collapse modes, such as punching shear failure of a flat slab-column joint that could lead to local collapse.

Volume 1, Chapter 6 provides additional discussion of non-simulated collapse modes. While it is possible to obtain additional ground motion pairs and perform additional analyses to replace the motions that produce collapse, that is not always necessary, and for shaking intensities where the collapse probability is high, it is impractical. The following approach is recommended when analytically predicted collapse is encountered in q or

more sets of the n ground motion pairs selected for a ground motion intensity:

1. Discard the analysis results from any ground motion pair that results in predictions of collapse.
2. If the remaining number of ground motion pairs for which collapse did not occur ($n-q$) is greater than or equal to 7, use the remaining ($n-q$) analyses to obtain estimates of demand at this ground motion intensity. No further analyses are required at this ground motion intensity level.
3. If the remaining number of ground motion pairs for which collapse did not occur ($n-q$) is less than or equal to 7, then additional ground motion pairs should be selected until at least 7 analyses that do not predict collapse are obtained. It is important to note that if the ground shaking intensity at which analysis is performed is associated with a collapse probability greater than 0.5, a very large number of analyses may be necessary to obtain 7 runs that do not predict collapse. At such ground motion intensities, building performance will be dominated by the probability of collapse. Therefore, it is recommended that ground motion intensities associated with collapse probabilities greater than 0.5 not be used to determine demand. Volume 1, Chapter 6 provides information on determining the collapse probability at different ground motion intensities.

Step 4. Estimate residual drift ratio values using peak transient drift ratios for each principal building direction as described above. Residual drift ratios should not be directly extracted from the response history analysis results as presently most response history analysis tools do not produce reliable estimates of residual drift ratio. Volume 1, Appendix C provides expanded discussion on this topic.

Step 5. Demand dispersions are assigned based on judgment as follows:

1. Select values from Volume 1, Table 5-1 and Volume 1, Table 5-2 (reproduced here as Table 3-1 and Table 3-2) for β_c and β_q
2. Calculate $\beta_m = \sqrt{\beta_c^2 + \beta_q^2}$
 β_m should not be taken greater than 0.5.
3. Assign a dispersion associated with residual drift, β_{RD} , equal to 0.8.

Table 3-1 Default Descriptions and Values for β_c

Building Definition and Construction Quality Assurance	β_c
<p><i>Superior Quality, New Buildings:</i> The building is completely designed and will be constructed with rigorous construction quality assurance, including special inspection, materials testing, and structural observation.</p> <p><i>Superior Quality, Existing Buildings:</i> Drawings and specifications are available and field investigation confirms they are representative of the actual construction, or if not, the actual construction is understood. Material properties are confirmed by extensive materials testing.</p>	0.10
<p><i>Average Quality, New Buildings:</i> The building design is completed to a level typical of design development; construction quality assurance and inspection are anticipated to be of limited quality.</p> <p><i>Average Quality, Existing Buildings:</i> Documents defining the building design are available and are confirmed by visual observation. Material properties are confirmed by limited materials testing.</p>	0.25
<p><i>Limited Quality, New Buildings:</i> The building design is completed to a level typical of schematic design, or other similar level of detail.</p> <p><i>Limited Quality, Existing Buildings:</i> Construction documents are not available and knowledge of the structure is based on limited field investigation. Material properties are based on default values typical for buildings of the type, location, and age of construction.</p>	0.40

Table 3-2 Default Descriptions and Values for β_q

Quality and Completeness of the Analytical Model	β_q
<p><i>Superior Quality:</i> The numerical model is robust over the anticipated range of response. Strength and stiffness deterioration and all likely failure modes are explicitly modeled. Model accuracy is established with data from large-scale component tests through failure.</p> <p><i>Completeness:</i> The mathematical model includes all structural components and nonstructural components in the building that contribute to strength or stiffness.</p>	0.10
<p><i>Average Quality:</i> The numerical model for each component is robust over the anticipated range of displacement or deformation response. Strength and stiffness deterioration is fairly well represented, though some failure modes are simulated indirectly. Accuracy is established through a combination of judgment and large-scale component tests.</p> <p><i>Completeness:</i> The mathematical model includes most structural components and nonstructural components in the building that contribute significant strength or stiffness.</p>	0.25
<p><i>Limited Quality:</i> The numerical model for each component is based on idealized cyclic envelope curves from ASCE/SEI 41-13 or comparable guidelines, where strength and stiffness deterioration and failure modes are not directly incorporated in the model.</p> <p><i>Completeness:</i> The mathematical model includes structural components in the seismic-force-resisting system.</p>	0.40

3.3.1.3 Input Response and Calculate Performance

For intensity-based assessment, PACT requires input of n demand vectors, one for each analysis, and the dispersion quantities discussed above. The

vectors should include values for each of the demand parameters required by the set of performance groups contained in the building performance model.

The basic steps for demand parameter input are:

Step 1. Identify the number of demand vectors, n , to be input. This is equal to the number of analyses that do not produce collapse.

Step 2. Input the value for each demand parameter for each level and direction, from each analysis in the **Structural Analysis Results** tab shown in Figure 3-3.

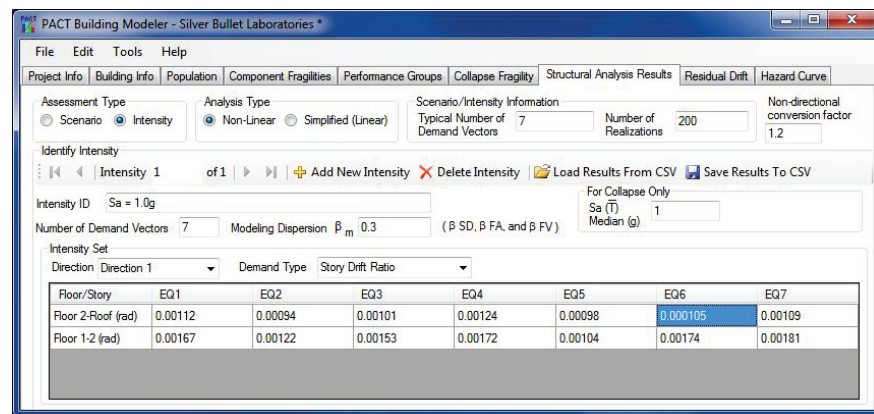


Figure 3-3 PACT Structural Analysis Results tab with response history drift input.

Step 3. Identify and input the value of $S_a(\bar{T})$ and the dispersion in the **Residual Drift** input tab shown in Figure 3-4.

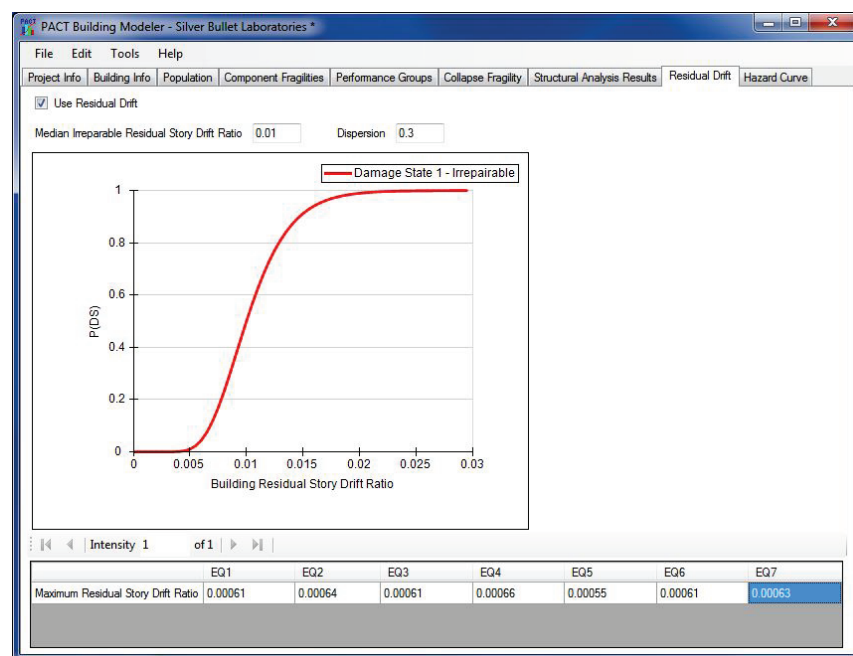


Figure 3-4 PACT Residual Drift input.

3.3.2 Simplified Analysis

3.3.2.1 Define Earthquake Hazards

The ground motion parameters used to assess response are the 5% damped elastic spectral response accelerations at the building's fundamental period in each of two orthogonal response directions, obtained by performing the following three steps:

Step 1. Identify the 5% damped elastic acceleration response spectrum that represents the desired intensity of shaking.

Step 2. Determine the building's fundamental translational period in each of two orthogonal directions (T_I^X, T_I^Y).

Step 3. Obtain $S_a(T_I^X)$ and $S_a(T_I^Y)$ from the selected spectrum.

3.3.2.2 Analyze Building Response

Analysis is used to produce estimates of story drift when the model is subjected to specified static lateral forces. These story drifts, together with estimates of the structure's yield strength and the peak ground acceleration and velocity are then used in regression equations to develop estimates of median story drift ratio, floor acceleration, and velocity in each of two orthogonal directions. Sections 3.3.2.2.1 through 3.3.2.2.6 below describe the steps of the procedure described in Volume 1, Section 5.3.2. Each step is illustrated with an example application using the 2-story reinforced masonry wall structure introduced in Section 2.6.1.

3.3.2.2.1 Determine Pseudo Lateral Force

Determine the total pseudo-lateral load, V , as defined in Volume 1, Equation 5-3 to be applied along each principal building axis (V_x, V_y):

$$V = C_I C_2 S_a(T_I) W_I$$

For this illustration $S_a(T_I)$ is taken as 1.0g, $T_I = 0.13$ seconds, and $W = 1133$ kips (per wall).

W_I is taken as $C_m W$ with C_m from Table 3-1 of ASCE/SEI 41-13. For the 2-story shear wall structure, C_m is 1.0 and thus $W_I = 1.0W = 1133$ kips.

C_I is an adjustment factor for inelastic displacements; given by Volume 1, Equation 5-5:

$$\begin{aligned}
C_l &= 1 + \frac{S-1}{0.04a} \quad \text{for } T_l \leq 0.2\text{sec} \\
&= 1 + \frac{S-1}{aT_l^2} \quad \text{for } 0.2 < T_l \leq 1.0\text{sec} \\
&= 1 \quad \text{for } T_l > 1.0\text{sec}
\end{aligned}$$

where T_l is the building's fundamental period in the direction under consideration; the coefficient a is obtained from Table 3-3.

Table 3-3 Values of coefficient a

ASCE/SEI 7-16 Site Class	a
A	130
B	130
C	90
D	60
E	60

and where S is a strength ratio given by Volume 1, Equation 5-6:

$$S = \frac{S_a(T_l)W}{V_{yl}}$$

In this equation, V_{yl} is the story yield strength in the direction under consideration. V_{yl} can be calculated using the following three different approaches.

Plastic Analysis Method

For a shear wall system, the equivalent lateral force distribution produces a base moment, M_0 , on the wall. The ratio of this moment to the base shear is designated the shear span, H_0 . Up until yielding at the wall's base occurs, the vertical force distribution procedure defined in the next step (Section 3.3.2.2.2) can be used to determine the shear span. The shear span can be used to define the relationship between base shear at yield and wall moment at yield.

Structural systems that include concentrically braced steel frames, low aspect ratio walls, or moment frames generally will not require an estimation of the vertical distribution of forces on the building. The calculation of story yield for these systems is predominantly dictated by the story shear only. For taller structures, the effects of overturning may reduce the story yield force and thus should be considered for all structural systems.

As defined in Section 3.3.2.2.2, the story force distribution of a 1 kip base shear is 0.63 kips at the roof and 0.37 kips at the second floor. For a 1 kip base shear, the flexural demand at the base of the walls will be:

$$M_o = 0.63(20) + 0.37(10) = 16.3 \text{ kip-ft}$$

Shear span is defined as $16.3/1 = 16.3$ feet

The calculated yield capacity using the nominal yield properties of one of the masonry walls in the building is equal to 5189k-l. The shear force is required to produce this moment is

$$\frac{M_y}{H_o} = \frac{5189}{16.3} = 318 \text{ kips}$$

Since the calculated value of V_{yl} is based on nominal rather than expected values, a conversion is required. The expected strength to nominal strength ratios given in ASCE/SEI 41-13 can be used for this purpose. In this case, flexural yielding will be controlled by the yield strength of the reinforcing steel, for which the expected strength to nominal strength ratio is 1.25, providing an estimated shear yield strength of $1.25(318 \text{ kips}) = 398 \text{ kips}$.

Nonlinear Static Analysis Method

Using the *SPO2IDA Tool* provided in Volume 3, the yield value, V_{yl} , can be calculated as 480 kips.

Using Judgment

The lower bound value V_{yl} is given by the following expression:

$$V_{yl} \geq \frac{1.55 S_a(T)W}{\frac{R}{I}}$$

where R , and I are the design coefficients for the building's structural system obtained from ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE, 2017).

For the example structure

$$S_a(T) = 1.0, W = 1133, R = 5, I = 1.0$$

$$V_{yl} \geq \frac{1.55 (1.0)(1133)}{5} = 351.2 \text{ kips}$$

The upper bound value V_{yl} is given by:

$$V_{yl} \leq \frac{\Omega_0 S_a(T) W}{\frac{R}{I}}$$

where Ω_0 is obtained from ASCE/SEI 7-16 as $\Omega_0=2.2$

$$V_{yl} = \frac{2.2(1.0)(1133)}{5} = 498.5 \text{ kips}$$

Summary

Plastic Analysis: $V_{yl}= 398$ kips

Nonlinear Static Analysis: $V_{yl} = 480$ kips

Judgment: $351.2 \text{ kips} \leq V_{yl} \leq 498.5 \text{ kips}$

For illustration in the continuation of this example, V_{yl} will be taken as 398 kips, based on the plastic analysis method above.

Returning to the calculation of S , $S = \frac{(1.0)(1133)}{398} = 2.85$

Since $T_l < 0.2s$

$$C_l = 1 + \frac{S-1}{0.04a}$$

The structure is located on Site Class D soil, therefore from Table 3-3, $a = 60$ and

$$C_l = 1 + \frac{2.85-1}{0.04(60)} = 1.77$$

For S greater than 1.0, C_2 (an adjustment factor for cyclic degradation) is given by Volume 1, Equation 5-7 as follows:

$$\begin{aligned} C_2 &= 1 + \frac{(S-1)^2}{32} && \text{for } T_l \leq 0.2 \text{ seconds} \\ &= 1 + \frac{1}{800} \frac{(S-1)^2}{T_l^2} && \text{for } 0.2 < T_l \leq 0.7 \text{ seconds} \\ &= 1 && \text{for } T_l > 0.7 \text{ seconds} \end{aligned}$$

Since $T_l \leq 0.2s$

$$C_2 = 1 + \frac{(S-1)^2}{32} = 1 + \frac{(1.85)^2}{32} = 1.11$$

thus $V = (1.77)(1.11)(1.0)(1133)$

$V = 2226$ kips

3.3.2.2.2 Estimate Median Story Drift Ratio and Dispersion

The median story drift ratio is estimated following the steps below.
Dispersion is estimated by using the default values given in Volume 1, Chapter 5.

Step 1. Determine the vertical distribution of force over the height of the building according to Volume 1, Equation 5-8 where F_x is the pseudo lateral load at each floor level x :

$$F_x = C_{vx}V$$

where C_{vx} is defined according to Volume 1, Equation 5-9:

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=2}^{N+1} w_i h_i^k}$$

where w_i is the lumped weight at floor level i , h_i (h_x) is the height above the effective base of the building to floor level I , and k is equal to 1.0 for T_I less than or equal to 0.5 seconds.

The floor and story heights are defined in accordance with Figure 3-5:

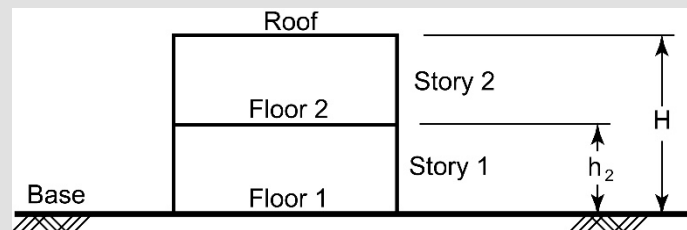


Figure 3-5 Definition of floor, story numbers and floor heights above grade for two-story building.

Thus $h_2 = 10\text{ft}$ and $H = 20\text{ft}$

The weight distribution is as illustrated in Figure 3-6:

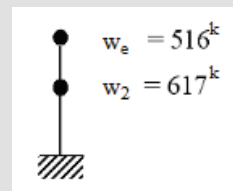


Figure 3-6 Lumped weight distribution.

The weight distribution and the story heights yield a ratio of 0.63 for the roof and 0.37 for the first floor.

$$F_R = 0.63(2226) = 1402.4 \text{ kips}$$

$$F_2 = 0.37(2226) = 823.6 \text{ kips}$$

Step 2. Compute floor displacements and story drift ratios by using a linear model with lateral loads F_R and F_2 .

Figure 3-7 illustrates the calculated floor displacements from linear analysis.

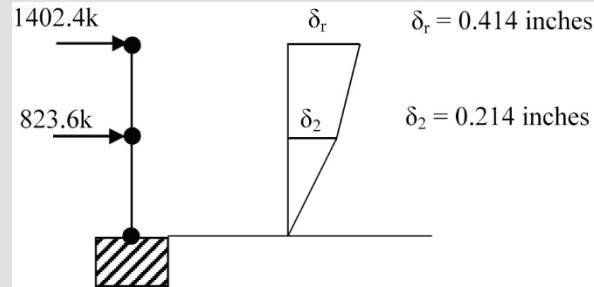


Figure 3-7 Results from linear analysis.

$$\Delta_1 = \frac{0.214}{(10)(12)} = 0.00178$$

$$\Delta_2 = \frac{0.414 - 0.214}{(E)(12)} = 0.00167$$

Calculated drift ratios are valid for both of the building's principal axes because of the building's symmetry (see Figure 2-12).

Step 3. Obtain estimates of median story drift ratio, Δ_i^* , at each story by correcting for inelastic behavior and higher modes using Volume 1, Equation 5-10:

$$\Delta_i^* = H_{\Delta_i}(S, T_l, h_i, H) \times \Delta_i \quad i = 1 \text{ to } N$$

where $H_{\Delta_i}(S, T_l, h_i, H)$ is the drift modification factor for story i computed using Volume 1, Equation 5-11:

$$\ln(H_{\Delta_i}) = a_0 + a_1 T_l + a_2 S + a_3 \frac{h_{i+1}}{H} + a_4 \left(\frac{h_{i+1}}{H} \right)^2 + a_5 \left(\frac{h_{i+1}}{H} \right)^3, \quad S \geq 1, i = 1 \text{ to } N$$

with T_l , S , and H as previously defined.

For a shear wall building of less than 10 stories tall, coefficients a_0 , a_1 , a_2 , a_3 , a_4 , and a_5 are determined from Volume 1, Table 5-4 as:

$$a_0 = 0.92, a_1 = -0.036, a_2 = -0.058, a_3 = -2.56, a_4 = 1.39, a_5 = 0$$

For $i=1$, $h_2 = 10$ feet, $H = 20$ feet:

$$\ln H_{\Delta_1} = 0.92 - 0.036(0.13) - 0.058(2.85) - 2.56 \left(\frac{10}{20} \right) + 1.39 \left(\frac{10}{20} \right)^2$$

$$\ln H_{\Delta_1} = -0.18248$$

$$H_{\Delta_1} = 0.833$$

$$\Delta_1^* = H_{\Delta_1}(\Delta_1) = 0.833(0.00178)$$

$$\Delta_1^* = 0.00148$$

For $i = 2$, $h_{roof} = H = 20$ feet:

$$\ln H_{\Delta_2} = 0.92 - 0.036(0.13) - 0.058(2.85) - 2.56\left(\frac{20}{20}\right) + 1.39\left(\frac{20}{20}\right)^2$$

$$\ln H_{\Delta_2} = -0.420$$

$$H_{\Delta_2} = 0.657$$

$$\Delta_2^* = H_{\Delta_2}(\Delta_2) = 0.657(0.00167)$$

$$\Delta_2^* = 0.00110$$

Step 4. As a result of uncertainty in ground motion, mathematical response modeling, and material property variability, the actual building response is likely to vary from estimated median response. These uncertainties are characterized as record-to-record variability, $\beta_{a\Delta}$, and modeling uncertainty, β_m . Total dispersion, β_{SD} , associated with the peak transient drift is given by Volume 1, Equation 5-19:

$$\beta_{SD} = \sqrt{\beta_{a\Delta}^2 + \beta_m^2}$$

Values for $\beta_{a\Delta}$, β_m , and β_{SD} are presented in Table 3-4. The first four columns of this table are excerpted from Volume 1, Table 5-6, and the last column is calculated with the above equation. For $T_l = 0.13$ s and $S = 2.85$, interpolation yields $\beta_{SD} = 0.47$.

Table 3-4 Default Dispersions for Story Drift

T_l (sec)	$S = \frac{S_a(T_l)W}{V_{yl}}$	$\beta_{a\Delta}$	β_m	β_{SD}
0.2	≤ 1.00	0.05	0.25	0.26
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67
0.35	≤ 1.00	0.1	0.25	0.27
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67

Table 3-4 Default Dispersions for Story Drift (continued)

T_1 (sec)	$S = \frac{S_a(T_1)W}{V_{y1}}$	$\beta_{a\Delta}$	β_m	β_{SD}
0.5	≤ 1.00	0.1	0.25	0.27
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67
0.75	≤ 1.00	0.1	0.25	0.27
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67
1	≤ 1.00	0.15	0.25	0.29
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67
1.5	≤ 1.00	0.15	0.25	0.29
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67
2.00+	≤ 1.00	0.25	0.25	0.35
	2	0.35	0.25	0.43
	4	0.4	0.35	0.53
	6	0.45	0.50	0.67
	≥ 8	0.45	0.50	0.67

3.3.2.2.3 Estimate Median Peak Floor Acceleration and Dispersion

Peak acceleration at the building base is taken as peak ground acceleration. At other floor levels, the median peak floor acceleration is estimated by following the steps below. Dispersion is estimated by using the default values given in Volume 1, Chapter 5.

Step 1. Obtain estimates of median peak floor acceleration, a_i^* , at each story above the building base by correcting peak ground accelerations using Volume 1, Equation 5-12:

$$a_i^* = H_{ai}(S, T, h_i, H) \times PGA \quad i = 2 \text{ to } N + 1$$

For this example, $PGA = 0.40g$.

H_{ai} is the acceleration correction factor for floor i given by Volume 1, Equation 5-13:

$$\ln(H_{ai}) = a_0 + a_1 T_l + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H} \right)^2 + a_5 \left(\frac{h_i}{H} \right)^3, \quad S \geq 1, i = 2 \text{ to } N + 1$$

with T_l , S , h_i and H as previously defined.

For a shear wall building of less than 10 stories tall, coefficients a_0 , a_1 , a_2 , a_3 , a_4 , and a_5 are found in Volume 1 Table 5-4 as:

$$a_0 = 0.66, a_1 = -0.15, a_2 = -0.084, a_3 = -0.26, a_4 = 0.57, a_5 = 0$$

For $i = 1$ (at grade):

$$a_1^* = PGA$$

$$a_1^* = 0.40g$$

For $i = 2$, $h_2 = 10$ ft, $H = 20$ ft

$$\frac{h_2}{H} = \frac{10}{20} = 0.5$$

$$\ln H_{a2} = 0.66 - 0.15(0.13) - 0.084(2.85) - 0.26(0.5) + 0.57(.5)^2$$

$$\ln H_{a2} = 0.4136$$

$$H_{a2} = 1.512$$

$$a_2^* = 1.512(0.4) = 0.605g$$

For $i = 3$ (roof), $h_{roof} = H = 20$ ft

$$\frac{h_3}{H} = \frac{20}{20} = 1.0$$

$$\ln H_{a3} = 0.66 - 0.15(0.13) - 0.084(2.85) - 0.26(1.0) + 0.57(1)^2$$

$$\ln H_{a3} = 0.7111$$

$$H_{a3} = 2.036$$

$$a_3^* = 2.036(0.4) = 0.814g$$

Step 2. Total dispersion, β_{FA} , associated with peak floor acceleration is given by Volume 1, Equation 5-20:

$$\beta_{FA} = \sqrt{\beta_{aa}^2 + \beta_m^2}$$

where values for β_{aa} and β_m are presented in Table 3-5. The first four columns of this table are excerpted from Volume 1, Table 5-6, and the last column is calculated with the above equation.

For $T_l = 0.13\text{s}$ and $S = 2.85$, interpolation yields $\beta_{FA} = 0.31$.

Table 3-5 Default Dispersions for Peak Floor Accelerations

T_l (sec)	$S = \frac{S_a(T_l)W}{V_{yl}}$	β_{aa}	β_m	β_{FA}
0.20	≤ 1.00	0.10	0.25	0.27
	2	0.10	0.25	0.27
	4	0.10	0.35	0.36
	6	0.10	0.50	0.51
	≥ 8	0.05	0.50	0.50
0.35	≤ 1.00	0.15	0.25	0.29
	2	0.15	0.25	0.29
	4	0.15	0.35	0.38
	6	0.15	0.50	0.52
	≥ 8	0.15	0.50	0.52
0.50	≤ 1.00	0.20	0.25	0.32
	2	0.20	0.25	0.32
	4	0.20	0.35	0.40
	6	0.20	0.50	0.54
	≥ 8	0.20	0.50	0.54
0.75	≤ 1.00	0.25	0.25	0.35
	2	0.25	0.25	0.35
	4	0.25	0.35	0.43
	6	0.25	0.50	0.56
	≥ 8	0.25	0.50	0.56
1.00	≤ 1.00	0.30	0.25	0.39
	2	0.30	0.25	0.39
	4	0.30	0.35	0.46
	6	0.30	0.50	0.58
	≥ 8	0.25	0.50	0.56
1.50	≤ 1.00	0.35	0.25	0.43
	2	0.35	0.25	0.43
	4	0.35	0.35	0.49
	6	0.35	0.50	0.61
	≥ 8	0.25	0.50	0.56

**Table 3-5 Default Dispersions for Peak Floor Accelerations
(continued)**

T_l (sec)	$S = \frac{S_a(T_l)W}{V_{yl}}$	β_{aa}	β_m	β_{FA}
2.00+	≤ 1.00	0.50	0.25	0.56
	2	0.45	0.25	0.51
	4	0.45	0.35	0.57
	6	0.40	0.50	0.64
	≥ 8	0.35	0.50	0.61

3.3.2.2.4 Estimate Median Peak Total Floor Velocity and Dispersion

The median peak total floor velocity is estimated by following the steps below. Dispersion is estimated by using the default values given in Volume 1, Chapter 5.

Step 1. A reference floor velocity at level i is obtained from Volume 1, Equation 5-18:

$$v_{si} = PGV + 0.3 \frac{T_l}{2\pi} \left(\frac{V_{yl}}{W_l / g} \Gamma_l \right) \left(\frac{\delta_i}{\delta_r} \right)$$

where:

$$T_l = 0.13 \text{ seconds}$$

$$V_{yl} = 398 \text{ kips}$$

$$\frac{W_l}{g} = 1.0W = \frac{1133}{g} \text{ kips}$$

$$\Gamma_l = \frac{W_l}{W} = 1.0$$

$$\delta_r = \frac{0.414}{(20)(12)} = 0.00173$$

Determine PGV

$$S_a(1) = 0.4g = 0.4(386 \text{ in} / \text{sec}^2) = 154 \text{ in} / \text{sec}^2 \text{ from site hazard data.}$$

$$S_v(1) = \frac{1S_a(1)}{2\pi} = \frac{(154 \text{ in} / \text{sec}^2)}{2\pi} = 24.5 \text{ in} / \text{sec}$$

$$PGV = \frac{S_v(1)}{1.65} = \frac{24.5 \text{ in} / \text{sec}}{1.65} = 14.5 \text{ in} / \text{sec}$$

For $i = 1$: For the first floor or grade level, peak total floor velocity equals the peak ground velocity.

$$v_{s1} = PGV = 14.5 \text{ in/sec}$$

For $i = 2$:

$$\Delta_1 = 0.00178$$

$$v_{s2} = 14.5 \text{ in/sec} + (0.3) \frac{0.13}{2\pi} \left(\frac{398}{1133/386} \right) (1.0) \left(\frac{0.00178}{0.00173} \right)$$

$$v_{s2} = 15.3 \text{ in/sec}$$

For $i = 3$:

$$\Delta_3 = 0.00167$$

$$v_{s2} = 14.5 \text{ in/sec} + (0.3) \frac{0.13}{2\pi} \left(\frac{398}{1133/386} \right) (1.0) \left(\frac{0.00167}{0.00173} \right)$$

$$v_{s2} = 15.3 \text{ in/sec}$$

Step 2. Obtain estimates of median peak total floor velocity by correcting for inelastic behavior and higher modes using Volume 1, Equation 5-16:

$$v_i^* = H_{vi}(S, T, h_i, H) \times v_{si} \quad i = 2 \text{ to } N + 1$$

where H_{vi} is the velocity modification factor for floor i , given by Volume 1, Equation 5-17:

$$\ln(H_{vi}) = a_0 + a_1 T_i + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H} \right)^2 + a_5 \left(\frac{h_i}{h} \right)^3, \quad S \geq 1, i = 2 \text{ to } N + 1$$

with S , T_i , h_i , and H as previously defined and $S > 1$.

For a shear wall building of less than 10 stories tall, coefficients a_0 , a_1 , a_2 , a_3 , a_4 , and a_5 are found in Volume 1, Table 5-4 as:

$$a_0 = -0.033, a_1 = -0.085, a_2 = 0.055, a_3 = -0.52, a_4 = 0.47, a_5 = 0$$

$$\text{For } i = 1, v_1^* = PGV = 14.5 \text{ in/sec}$$

$$\text{For } i = 2, h_2 = 10 \text{ feet}$$

$$\ln(H_{v_2}) = -0.033 - 0.085(1.13) + 0.055(2.85) - 0.52 \left(\frac{10}{20} \right) + 0.47 \left(\frac{10}{20} \right)^2$$

$$\ln(H_{v_2}) = -0.0298$$

$$H_{v_2} = 0.971$$

$$v_{s2}^* = (0.971) 15.3 \text{ in/sec} = 14.9 \text{ in/sec}$$

$$\text{For } i = 3, h_{roof} = H = 20 \text{ feet}$$

$$\ln(H_{v_3}) = 0.0627$$

$$H_{v_3} = 1.065$$

$$v_{s3}^* = (1.065)15.3\text{in/sec} = 16.3\text{in/sec}$$

Step 3. Total dispersion, β_{FV} , associated with peak total floor velocity is given by Volume 1 Equation 5-21:

$$\beta_{FV} = \sqrt{\beta_{av}^2 + \beta_m^2}$$

Values for β_{av} , β_m , and β_{FV} are presented in Table 3-6. The first four columns of this table are excerpted from Volume 1, Table 5-6, and the last column is calculated with the above equation. For $T_l \leq 0.2\text{s}$ and $S = 2.85$, interpolation yields $\beta_{FV} = 0.55$.

Table 3-6 Default Dispersions for Total Peak Floor Velocity

T_l (sec)	$S = \frac{S_a(T_l)W}{V_{yl}}$	β_{av}	β_m	β_{FV}
0.20	≤ 1.00	0.50	0.25	0.56
	2	0.51	0.25	0.57
	4	0.40	0.35	0.53
	6	0.37	0.50	0.62
	≥ 8	0.24	0.50	0.55
0.35	≤ 1.00	0.32	0.25	0.41
	2	0.38	0.25	0.45
	4	0.43	0.35	0.55
	6	0.38	0.50	0.63
	≥ 8	0.34	0.50	0.60
0.50	≤ 1.00	0.31	0.25	0.40
	2	0.35	0.25	0.43
	4	0.41	0.35	0.54
	6	0.36	0.50	0.62
	≥ 8	0.32	0.50	0.59
0.75	≤ 1.00	0.30	0.25	0.39
	2	0.33	0.25	0.41
	4	0.39	0.35	0.52
	6	0.35	0.50	0.61
	≥ 8	0.30	0.50	0.58
1.00	≤ 1.00	0.27	0.25	0.37
	2	0.29	0.25	0.38
	4	0.37	0.35	0.51
	6	0.36	0.50	0.62
	≥ 8	0.34	0.50	0.60

Table 3-6 Default Dispersions for Total Peak Floor Velocity (continued)

T_1 (sec)	$S = \frac{S_a(T_1)W}{V_{yI}}$	β_{av}	β_m	β_{EV}
1.50	≤ 1.00	0.25	0.25	0.35
	2	0.26	0.25	0.36
	4	0.33	0.35	0.48
	6	0.34	0.50	0.60
	≥ 8	0.33	0.50	0.60
2.00+	≤ 1.00	0.28	0.25	0.38
	2	0.21	0.25	0.33
	4	0.25	0.35	0.43
	6	0.26	0.50	0.56
	≥ 8	0.26	0.50	0.56

3.3.2.2.5 Estimate Median Residual Story Drift Ratio and Dispersion

The approach for estimating median residual story drift ratio presented in Volume 1, Section 5.4 is summarized in Table 3-7 for different structural systems and illustrated below.

Table 3-7 Procedures for Estimating Median Story Drift Ratio at Yield

Structural System	Procedure
Steel concentrically braced frames and low aspect ratio wall systems	Calculate story drift ratio at which the story shear equals the expected yield strength of the braces or shear strength of the walls
Moment frames	Calculate story drift ratio which produces a story shear that results in: <ul style="list-style-type: none"> beams or columns reach plastic moment capacity (include axial forces) beam-column joint reaches its expected yield strength in shear
Slender shear walls (governed by flexural yielding)	Calculate the story drift ratio at which the walls attain their expected flexural strength using a lateral force distribution that reflects the dynamic response of the building

Step 1. Estimate of the median residual drift ratio is generated as follows:

$$\Delta_r^* = 0 \quad \Delta_r^* \leq \Delta_y$$

$$\Delta_r^* = 0.3(\Delta_i^* - \Delta_y) \quad \Delta_y < \Delta_i^* < 4\Delta_y$$

$$\Delta_r^* = (\Delta_i^* - 3\Delta_y) \quad \Delta_i^* \geq 4\Delta_y$$

where Δ_t^* is the median transient drift ratio and Δ_y is the median story drift ratio calculated at yield.

Following the guidance provided in Table 3-7 for a shear wall system (governed by flexural yielding), Δ_y can be estimated with $\Delta_t^* = 0.00148$, $\Delta_2^* = 0.00110$, and $V_{yl} = 398$ kips, where V_{yl} equals the base shear at which the base of the wall is expected to reach its flexural yield capacity and the lateral force distribution reflects the dynamic response of the building.

Using the linear model, the building displacements can be scaled for a base shear of 398 kips as follows:

$$\delta_{ry} = \frac{0.414(398)}{2226} = 0.074 \text{ inches}$$

$$\delta_{ly} = \frac{0.214(398)}{2226} = 0.038 \text{ inches}$$

$$\Delta_y = \frac{0.038}{10(12)} = 0.00032$$

$$\frac{\Delta_t^*}{\Delta_y} = \frac{0.00148}{0.00032} = 4.63$$

Residual drift ratios are thus predicted as follows:

$$\Delta_{r1}^* = 0.00148 - 3(0.00032) = 0.00052$$

$$\Delta_{r2}^* = 0.00110 - 3(0.00032) = 0.00014$$

Note that the simplified analysis illustrated in this example was developed for application to structures with peak transient drift demands less than or equal to 4 times the yield drift. Beyond this level, simplified analysis may become less valid. If the building is experiencing such large inelastic demand, the nonlinear analysis method should be considered in order to obtain more valid results.

Step 2. The total dispersion associated with median values of residual drift ratio should be taken as $\beta_{RD} = 0.8$. This value includes both β_a and β_m .

3.3.2.3 Input Response and Calculate Performance

Simplified building response analyses produce estimated median values of peak story drift ratios, Δ_t^* , peak total floor accelerations, a_t^* , peak total floor velocities, v_{si}^* , and residual drift ratios in each principal building response direction. PACT uses this information to make damage state assessments for all building components contained in the building model. All demands

except residual drift are input via the **Structural Analysis Results** tab, as shown in Figure 3-8.

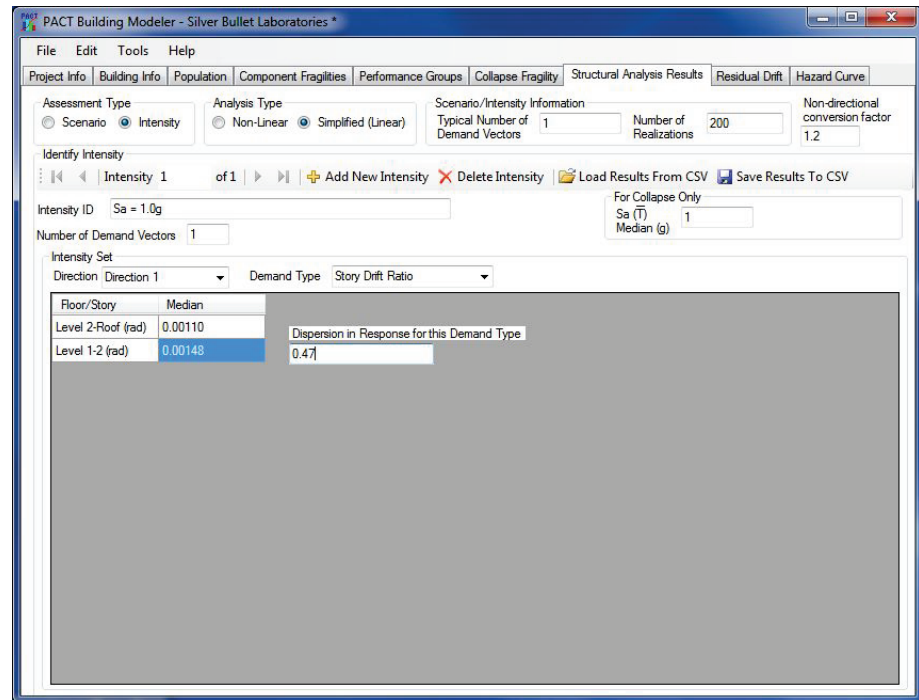


Figure 3-8 PACT Structural Analysis Results tab, intensity-based assessment.

Radio buttons and fields on the upper portion of the tab should be modified by the user to reflect:

- **Assessment Type:** Intensity
- **Analysis Type:** Simplified (Linear)
- **Typical Number of Demand Vectors:** This number indicates to PACT the total number of demand vectors that may be input for each intensity for which an assessment will be performed. The actual number of vectors input in the lower portion of the screen can be less. Each intensity included in the assessment can have a different number of demand vectors.
- **Number of Realizations:** PACT uses a Monte Carlo process to determine the probability of incurring consequences. If an insufficiently large number of realizations are performed for each demand vector, the indicated probability distribution may be quite inaccurate and can change significantly each time PACT is run with the same data. The PACT default setting is 200 realizations. This number of realizations has generally produced stable results for repair cost and repair time. At least 500 realizations should be used for obtaining estimates for casualties and unsafe placards. Use of larger numbers of realizations will increase

PACT execution time slightly, however, both storage time and space can increase significantly.

- **Non-Directional Conversion Factor:** This factor sets the estimated non-directional value of demand (story drift ratio, acceleration) as a multiple of the maximum value of either of the directions. It is set at a default value of 1.2, which is believed appropriate for most structures.

Under the **Identify Intensity** section, the user will need to depress the + **Add New Intensity** button to prompt the setup for inputting intensity analysis results. The user can then input the **Intensity ID** to identify the intensity in the output files.

The spectral acceleration value at the fundamental building period in each direction is entered to enable PACT to determine the probability of collapse.

When nonlinear response history analyses are performed, demand vectors are first input in the **Number of Demand Vectors** field, then the building **Direction** and the **Demand Type** are identified. The number of demand vectors includes the results to be input for drift, floor acceleration, and floor velocity in each building direction. The user can also input other demand parameters assignable to direction 1, direction 2, or non-directional. For the simplified analysis approach, there will only be one demand vector containing drifts, floor accelerations and floor velocities for each building direction and each floor or story. Results should be input for all demand types and directions that are used by the fragility specifications selected to define damageable building components.

For each demand vector, the associated **Dispersion** is input to the right of the median values. Results are input from the top of the building to the bottom.

Table 3-8 summarizes the results obtained for median and dispersion values of peak story drift ratios for a 2-story reinforced masonry structure in Section 3.3.2.2.2. The values for direction 1 are utilized in Figure 3-8.

Table 3-8 Drift Ratio Vectors

Floor	Story	Direction 1		Direction 2	
		Δ^*		Δ^*	
		θ	β	θ	β
2 to 3	2nd	0.00110	0.47	0.00110	0.47
1 to 2	1st	0.00148	0.47	0.00148	0.47

The maximum residual drift value and dispersion are input for each intensity in the bottom row of the **Residual Drift** tab, as shown in Figure 3-9. This

portion of the **Residual Drift** tab is not available for data entry until the structural analysis results have been input on the **Structural Analysis Results** tab.

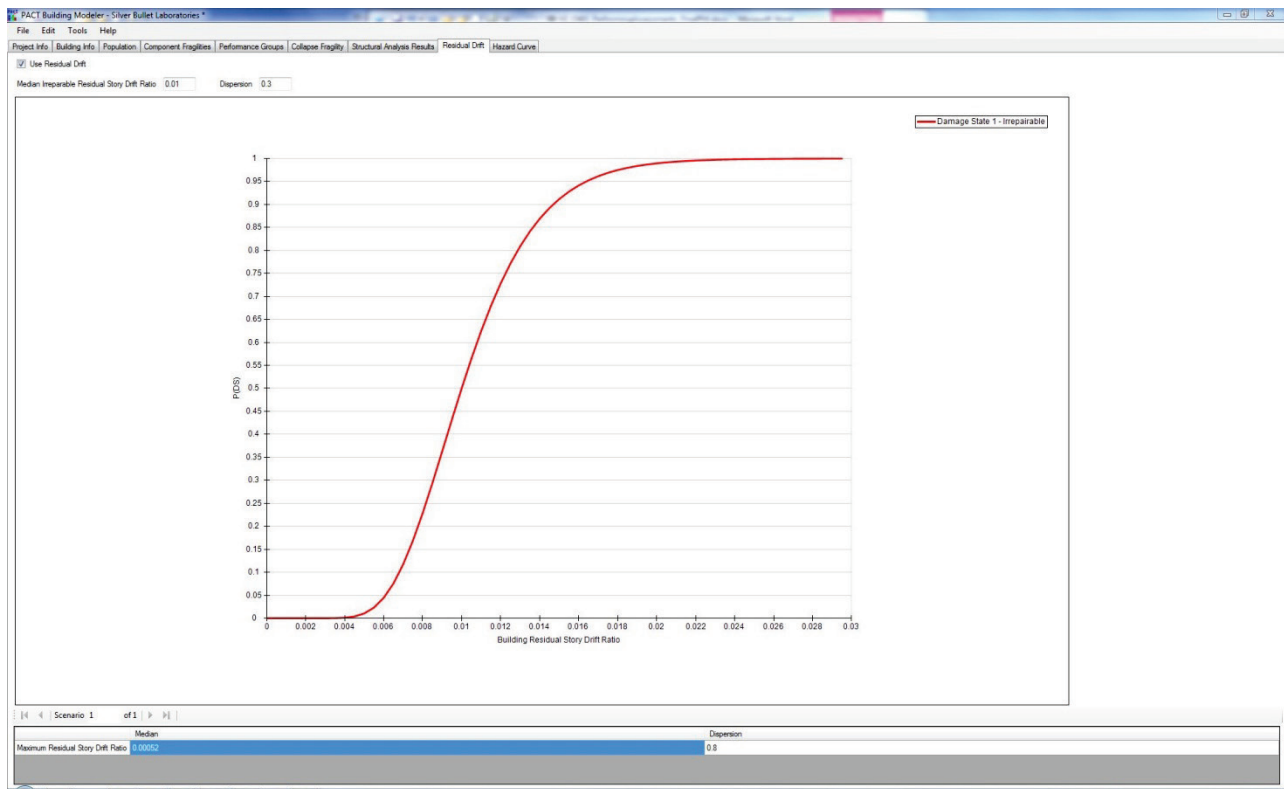


Figure 3-9 PACT Residual Drift tab.

3.3.3 Review Results

After completing the performance model and analysis results entry, the building model is saved, and PACT can execute the performance assessment. This process is initiated by selecting the **Evaluate Performance** button (Figure 3-10) on the **PACT Control Panel**. This will bring up the **PACT Engine** window (Figure 3-11).

The **File** menu in this window is used to open the building project file, and the **Run Evaluation** button is pressed. Upon completion, the user can save the results for review. The results can be reviewed by pressing the **Examine Results** button in the **PACT Control Panel** (See Figure 3-10).

Figure 3-12 and Figure 3-13 display the PACT output representative of laboratory occupancy with intensity-based assessment. Other performance measures are available from the tabs at the top of the results screen (**Casualties**, **Repair Time**, and **Unsafe Placards**). More detailed results can be viewed in the **Data Drill Down and Exports** tab.

PACT provides a range of options for viewing assessment results on the screen or printing out hard copy reports. In addition to providing composite results considering all performance groups and demand input from both building directions, PACT can parse results by performance group, direction, story level, and realization. Please refer to Appendix C for additional information regarding the use of PACT.

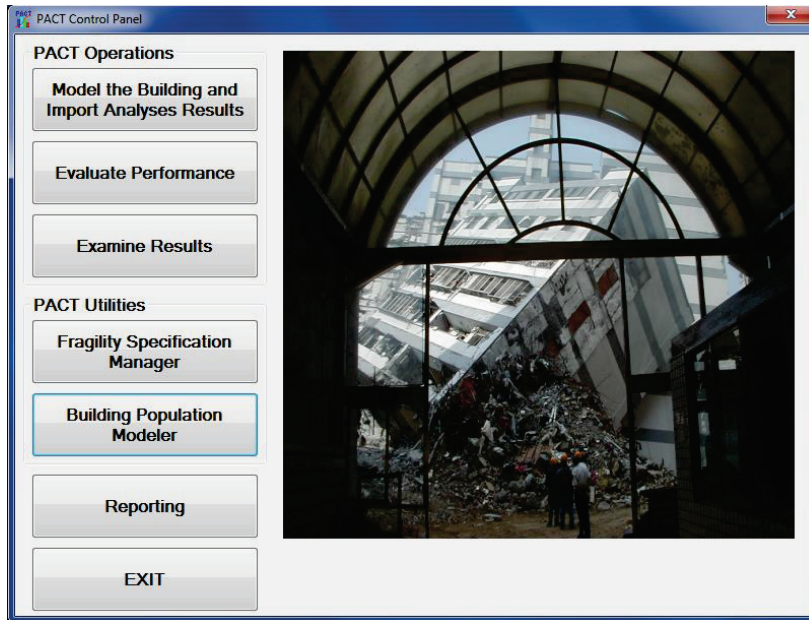


Figure 3-10 PACT Control Panel.

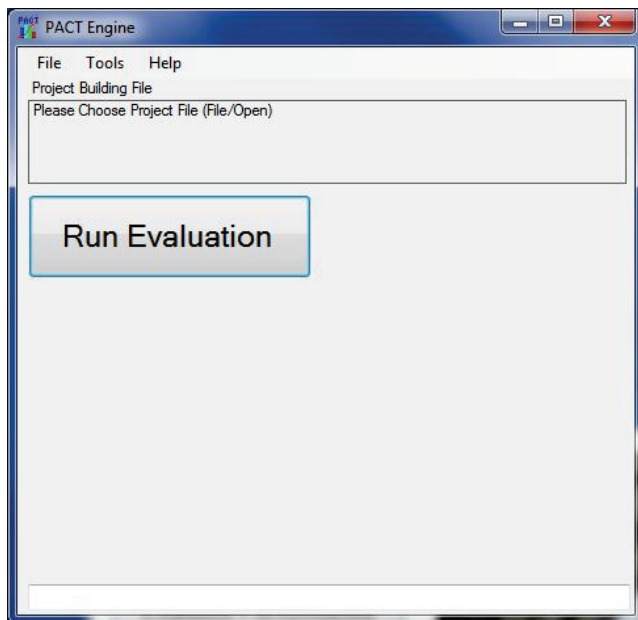


Figure 3-11 PACT Engine window.

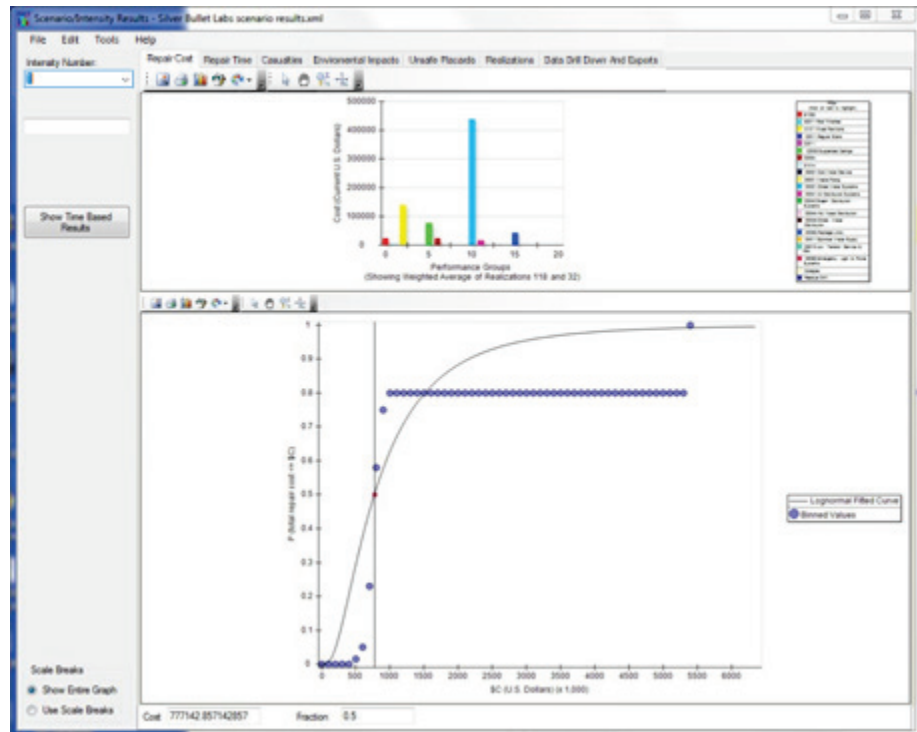


Figure 3-12 PACT Repair Cost tab.

The upper portion of the **Repair Cost** tab (Figure 3-12) illustrates the contribution to repair cost attributable to each performance group. By selecting the **Realizations** button, a graphic representation of performance group contributors to the repair cost for each realization can be viewed. Figure 3-13 illustrates this output format.

Figure 3-13 indicates that collapse occurred for realizations 160 through 200. Realizations 0 through 159 did not result in collapse and the individual performance group contributions are as shown in the upper half of Figure 3-12. Figure 3-14 illustrates the same result shown in the upper half of Figure 3-12 with the components grouped into the major fragility specification categories. For this intensity, chilled water components are the primary contributor to repair costs for the realization at which median loss occurs. The contribution to loss for other realizations can be found by changing the **Fraction** field at the lower left-hand corner of the screen to any value between 0 and 1. Options for restructuring performance group viewing can be found under the **Tools** menu at the top of the screen.

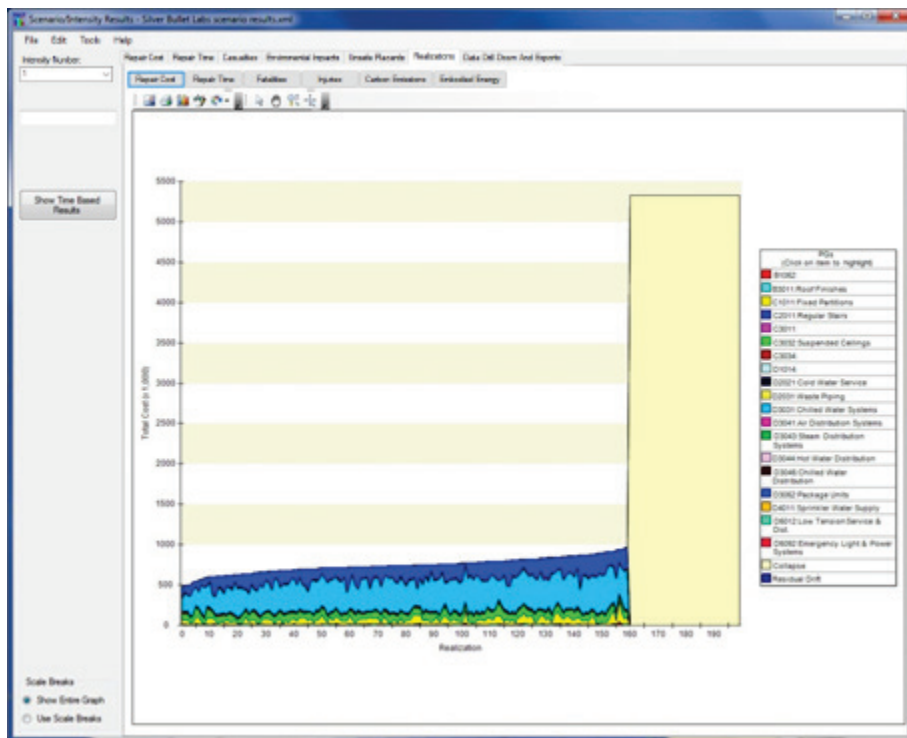


Figure 3-13 PACT Realizations tab.

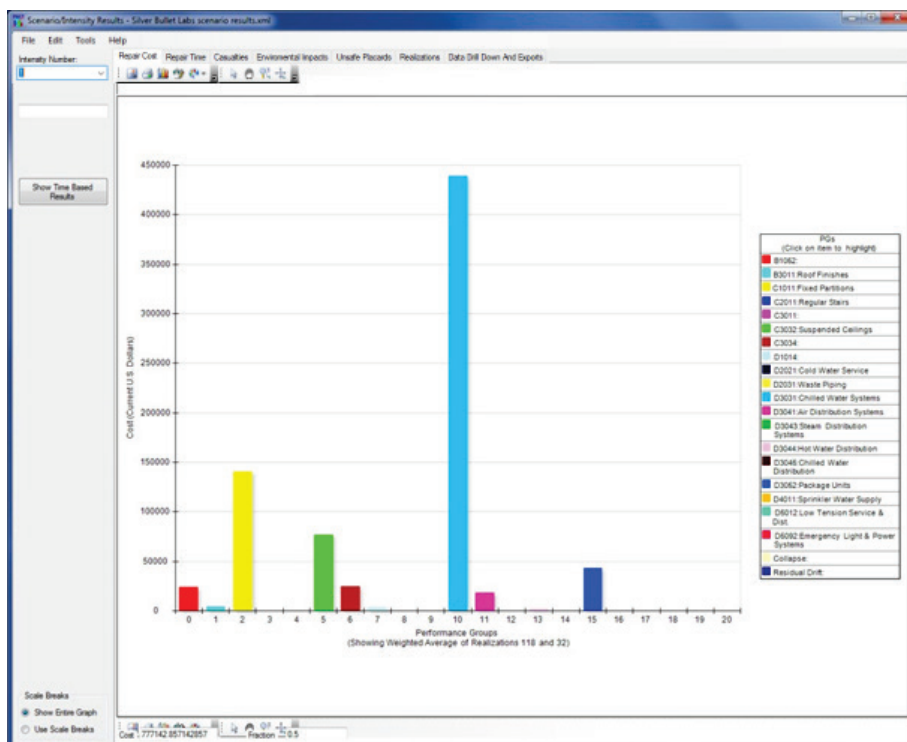


Figure 3-14 PACT Repair Cost tab showing repair cost by performance group.

The lower half of Figure 3-12 presents the repair cost probability distribution. The median value is reported as \$777,142.86. Any repair cost

(or non-exceedance probability) can be entered into the boxes below the loss curve and the corresponding non-exceedance probability (or repair cost) will be reported upon pressing the “Enter” key. Note that as the costs and non-exceedance probabilities are changed, the performance group contributions may change as well.

Under the **Data Drill Down and Exports** tab, numerous options exist for viewing and exporting data. Figure 3-15 shows this tab with data for a representative 4-story laboratory building. By pressing the **View Drilldown Page** button, the user can see the results for each realization, for each floor, each direction, and each performance group.

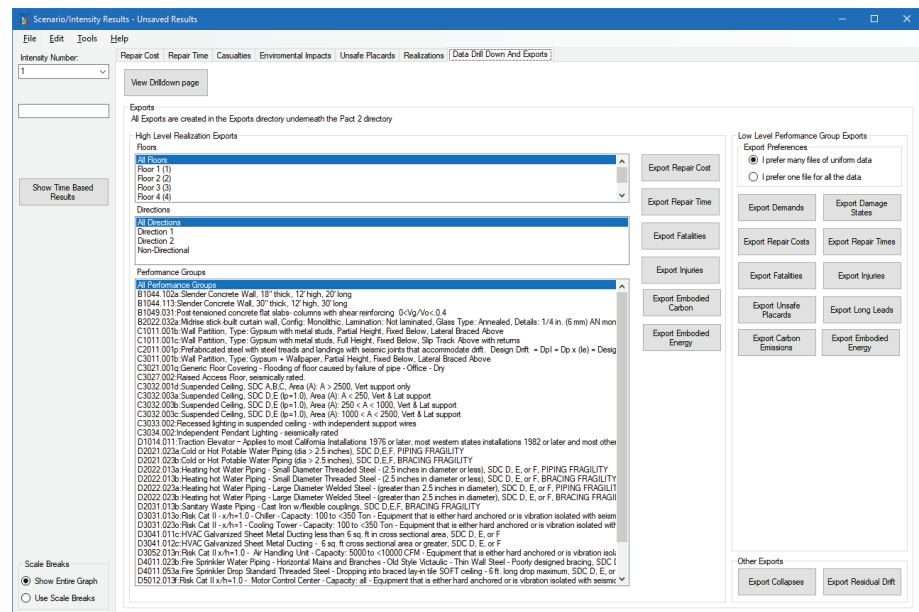


Figure 3-15 PACT Data Drill Down and Exports tab.

The same output and viewing options are available for assessments performed using nonlinear response history analysis.

3.4 Scenario-Based Assessment

Scenario-based assessment enables calculation of performance for user-specified combinations of earthquake magnitude and site-to-source distance. The selected earthquake magnitude and site-to-source distance are converted into a shaking intensity distribution by a ground motion prediction equation (or attenuation relationship) that is developed by performing regression analyses on the values of intensity parameters obtained from strong motion recordings of past earthquakes against distance, magnitude, and other parameters. The estimate may include consideration of many variables including fault type, soil type, and other factors.

Most ground motion prediction models provide a median estimate of intensity and a measure of uncertainty. Once intensity is defined, the performance assessment process is completed in a manner nearly identical to that for intensity-based assessment.

There can be considerable variation in the predictions among attenuation relationships depending upon the site conditions and the target scenario. Volume 1, Chapter 4 and Volume 1, Appendix B provide discussion and guidance for selecting an attenuation relationship for scenario-based assessment.

This example utilizes the Open Seismic Hazard Analysis website (<http://www.opensha.org>, last accessed March 15, 2018) that provides a downloadable attenuation relationship plotter which can be used to generate median spectra and dispersions for the following attenuation relationships for any magnitude-distance pair selected:

- Boore and Atkinson
- Campbell and Bozorgnia
- Chiou and Youngs

It is noted that use of the Open Seismic Hazard Analysis (OpenSHA) tool may require a revision to computer security settings to provide the results. Alternatively, U.S. Geological Survey (USGS) has developed the *Unified Hazard Tool* that can be used to develop seismic hazard curves in most situations. The USGS tool is available at <https://earthquake.usgs.gov/hazards/interactive/> (last accessed March 15, 2018).

In 2014, a new set of ground motion prediction equations (Next Generation Attenuation Relationships for Western U.S., NGA-West2) were developed and used in the development of the seismic design maps in ASCE/SEI 7-16. These new equations can be downloaded from the PEER Ground Motion Database, available at <http://peer.berkeley.edu/ngawest2/> (last accessed March 15, 2018).

Some decision makers will be interested in a building's performance if a repeat occurrence of a historic event occurs. Parameters defining many historic events are available from numerous sources including searchable catalogs at <https://earthquake.usgs.gov/earthquakes/search/> (last accessed March 15, 2018).

Some decision makers may desire performance assessments for worst case scenarios. The USGS posts information on best estimate maximum magnitudes for active faults in the Western United States and the Inner

Mountain seismic region at <http://earthquake.usgs.gov/hazards/qfaults/> (last accessed March 15, 2018).

3.4.1 Nonlinear Response History Analysis

3.4.1.1 Define Earthquake Hazards

Volume 1, Chapter 4 presents a procedure for selecting and scaling ground motions to a median spectrum obtained from the ground motion prediction equation. The prediction model uncertainty obtained is assigned as an additional component of total dispersion. This procedure is illustrated here and involves the following steps:

Step 1. Determine the building's fundamental translational periods in each of two principal directions, T_l^x, T_l^y .

Step 2. Determine the average first mode period \bar{T} as the average of T_l^x and T_l^y if the mode shapes are uncoupled and as the larger of T_l^x or T_l^y if the mode shapes are coupled.

Step 3. Estimate the average wave velocity, V_{s30} , in the upper 30 meters (100 ft.) of soil at the site.

Step 4. Select an appropriate attenuation relationship that best matches the fault characteristics, regional geology, and site conditions for the scenario event and building site. Downloadable attenuation functions are available at <http://www.opensha.org> and at <https://ngawest2.berkeley.edu/>.

Step 5. Determine the values of variables used in the selected attenuation relationship.

Step 6. Use the attenuation relationship to generate the median value of spectral acceleration and associated period-dependent dispersion over the full range of potential structural periods (0.01 to 5 seconds).

Step 7. If the attenuation relationship does not include consideration of site characteristics and class, adjust the spectrum to account for these effects, using site response analysis, site class coefficients contained in ASCE/SEI 7-16, or other suitable adjustment factors.

Step 8. Calculate the structural period range of interest for spectral scaling as:

$$T_{min} = 0.2\bar{T}$$

$$T_{max} = 2.0\bar{T}$$

Step 9. Select n ground motion pairs with 5% damped geomean spectral shape similar to the spectrum generated in Steps 6 and 7 over the period range T_{min} to T_{max} .

Step 10. Amplitude scale the suite of records to match the target spectrum.

Volume 1, Appendix B presents a second, alternative procedure with which ground motions are selected to represent the dispersion in intensity obtained from the ground motion prediction equation.

3.4.1.2 Analyze Building Response

Per Section 3.4.1.1, n analyses using the n scaled ground motion pairs are performed. Determination of median values and dispersions for peak transient drift ratio, peak floor acceleration, and residual drift ratio are illustrated in the following subsections.

3.4.1.2.1 Determine Peak Transient Drift Ratios, Peak Floor Accelerations, Peak Total Floor Velocities, and Residual Drifts

Step 1. Execute an analysis of the structure for each ground motion pair.

Step 2. Extract the peak transient drift ratios, peak total floor accelerations and velocities from each analysis for each principal building direction.

Note that many computer programs commonly used to perform nonlinear dynamic analysis do not provide total floor acceleration or velocity. Floor velocity (relative to the ground) can be obtained as the first derivative of floor displacement, and can be computed with the following equation for each time step:

$$v_{i,j} = \frac{x_{i,j} - x_{i,j-1}}{\Delta t}$$

where $v_{i,j}$ is the floor velocity at floor i , at time step j , and $x_{i,j}$ and $x_{i,j-1}$ are the displacements of floor i at time steps j and $(j-1)$, respectively and Δt is the time step.

If a velocity history for the ground motion is available, total velocity can be obtained as the vector sum of the ground velocity and floor velocity at each time step. If a velocity series for the ground motion is not available, maximum floor velocity can be approximated from the equation:

$$V_{jmax} = \sqrt{(v_{jmax})^2 + PGV^2}$$

where V_{jmax} is the approximate maximum total floor velocity at floor j , v_{jmax} is the maximum of the relative floor velocities at floor j , and PGV is the peak ground velocity.

If the computer software used to perform dynamic analyses does not provide total acceleration, it can be derived by taking the vector sum of floor acceleration relative to the ground and ground acceleration at each time step. Floor acceleration relative to the ground can be obtained by taking the second derivative of the floor displacement history from the formula:

$$a_{i,j} = \frac{v_{i,j} - v_{i,j-1}}{\Delta t}$$

where $v_{i,j}$ and $v_{i,j-1}$ are the floor velocities at floor i , for steps j and $j-1$.

Step 3. Estimate residual drift ratio in each direction from the peak transient drift ratio as follows:

$$\begin{aligned} \Delta_r &= 0 & \text{for } \Delta \leq \Delta_y \\ \Delta_r &= 0.3(\Delta - \Delta_y) & \text{for } \Delta_y < \Delta < 4\Delta_y \\ \Delta_r &= (\Delta - 3\Delta_y) & \text{for } \Delta \geq 4\Delta_y \end{aligned}$$

where

Δ = values of median story drift ratio determined in Step 2

Δ_y = median story drift ratio calculated at yield

As noted in Section 3.3.1, residual drifts should not be directly extracted from the response history simulation results.

3.4.1.2.2 Generate Simulated Response Dispersions

Assign demand dispersion values for β_c and β_q from Table 3-1 and Table 3-2. Modeling dispersion, β_m , is calculated as $\sqrt{\beta_c^2 + \beta_q^2}$. For scenario assessments, an additional uncertainty is introduced to reflect the variability associated with the predictive ability of the attenuation relationship. The dispersions associated with the attenuation relationship can be used directly for β_{gm} , or if these are not evident, the values of Table 3-9 can be used.

The plot in Figure 3-16, obtained from the *Attenuation Relationship Plotter* application available on <http://www.opensha.org>, illustrates the period-dependent dispersion for the example application in Section 3.4.2.1. For the example short-period structure ($\bar{T} = 0.13$ s), the corresponding dispersion is 0.57. This value compares favorably with the default value provided in Table 3-10 for Western North America, 0.60.

Table 3-9 Default Dispersions Ground Motion Variability, β_{gm}

T_r (sec)	Western North America	Central and Eastern United States	Pacific Northwest
<0.20	0.60	0.53	0.80
0.35	0.60	0.55	0.80
0.5	0.61	0.55	0.80
0.75	0.64	0.58	0.80
1.0	0.65	0.60	0.80
1.50	0.67	0.60	0.85
≥ 2.0	0.70	0.60	0.90

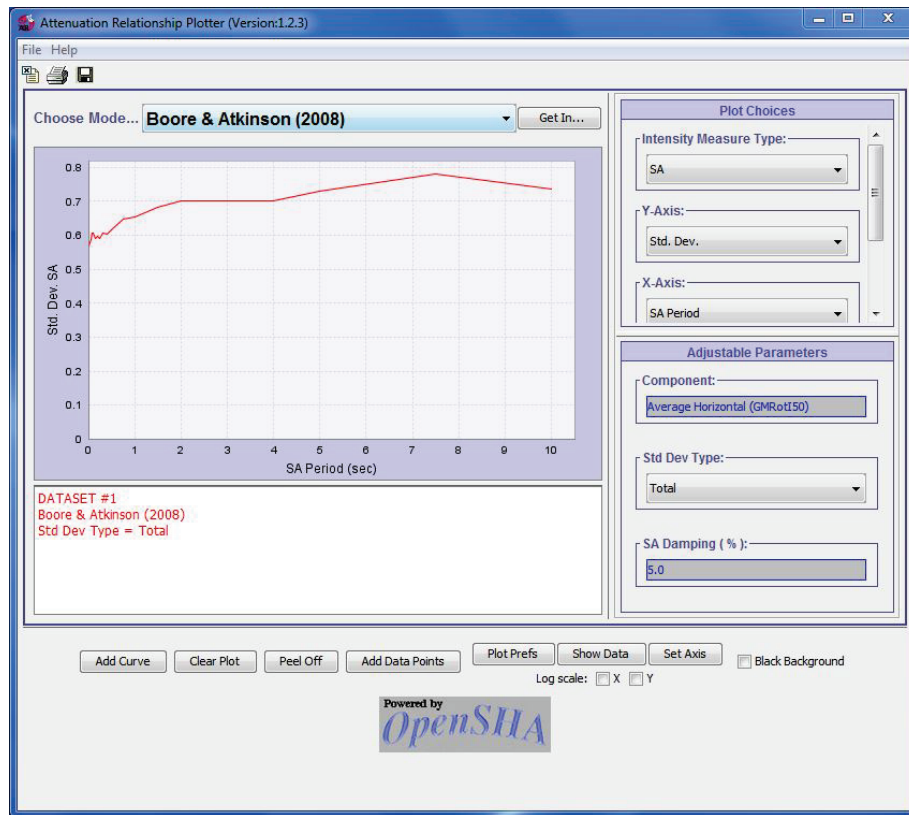


Figure 3-16 Standard deviation of S_a vs. T attenuation plot from <http://www.opensha.org>.

Next, the ground motion dispersion, β_{gm} , is combined with β_c and β_q to produce β_m for use in scenario assessments as:

$$\beta_m = \sqrt{\beta_c^2 + \beta_q^2 + \beta_{gm}^2}$$

If alternate procedures for scaling ground motion records are used for analysis, β_{gm} need not be included in the total assigned dispersion since its effects have been captured directly in the calculation process.

3.4.1.3 Input Response and Calculate Performance

Structural analysis results are entered into PACT in a manner similar to that for intensity-based assessment. Figure 3-17 illustrates the input for direction 1 drift values from analyses performed with 7 ground motion pairs scaled to the scenario target spectrum. The modeling dispersion, β_m , includes the β_{gm} term.

Floor/Story	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7
Floor 2-Roof (rad)	0.0112	0.00094	0.00101	0.00124	0.00098	0.00105	0.00109
Floor 1-2 (rad)	0.00167	0.00122	0.00153	0.00172	0.00104	0.00174	0.00159

Figure 3-17 PACT Structural Analysis Results tab, scenario-based assessment, nonlinear analysis.

3.4.2 Simplified Analysis

3.4.2.1 Define Earthquake Hazards

The simplified analysis method requires spectral response accelerations obtained from a 5% damped elastic response spectrum consistent with the selected magnitude and distance scenario. This requires selection and use of a ground motion prediction equation to define the scenario response spectrum. Volume 1, Chapter 4 and Volume 1, Appendix B provide information on selection and use of these models. The basic steps are illustrated below:

The 2-story reinforced masonry wall building previously used to illustrate the simplified analysis approach for intensity-based assessment is used in this example. Assumed conditions are:

- Site soil class D
- Distance to fault (closest horizontal distance to the vertical projection of rupture), $r_{jb} = 20$ km
- Earthquake magnitude, $M_w = 6.5$
- Strike-slip fault

Step 1. Estimate the average shear wave velocity in the upper 30 meters of site soils:

$$V_{s30} = 800 \text{ ft/s} = 243.8 \text{ m/s}$$

Step 2. Select an appropriate attenuation relationship that best matches the fault characteristics, regional geology, and site conditions of the scenario event and the reference building site.

Boore & Atkinson 2008 function is selected on the *Attenuation Relationship Plotter* application available at <http://www.opensha.org>, and the above data are input. Figure 3-16 and Figure 3-18 indicate the standard deviation and median prediction for S_a , respectively.

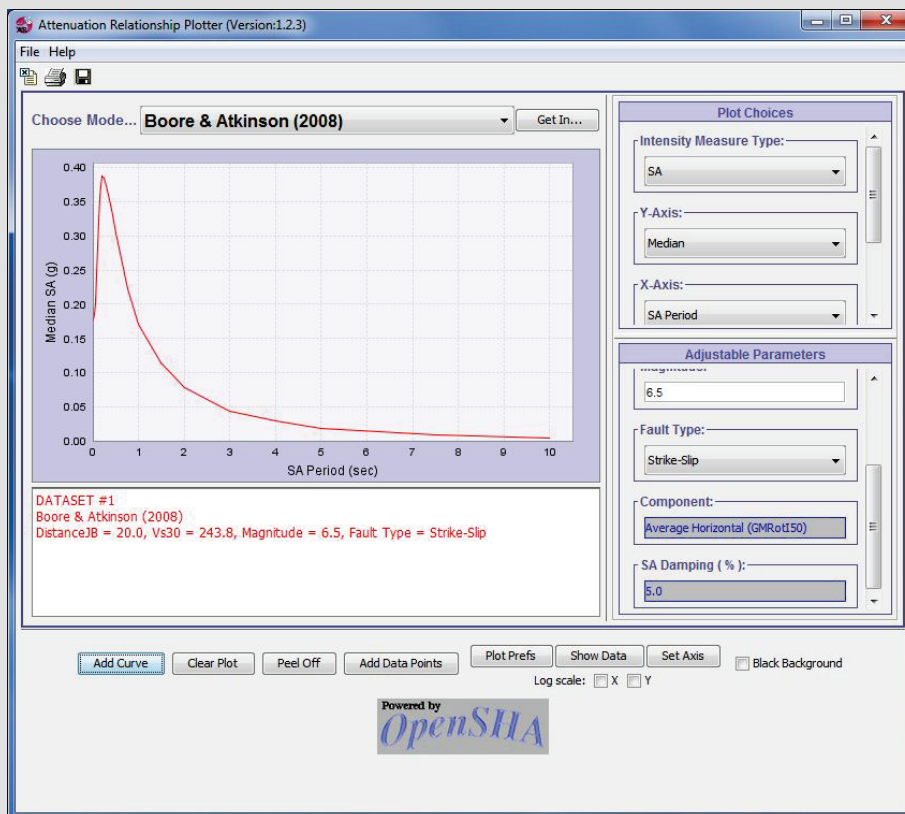


Figure 3-18 Median S_a vs. T attenuation plot from <http://www.opensha.org>.

Step 3. Define the value of variables used in the selected attenuation relationship.

From previous analysis, $T_l^X = T_l^Y = 0.13$ seconds.

Step 4. Use the attenuation relationship to generate the median value of spectral acceleration and associated period dependent dispersion over the full

range of potential structural periods (0.01 to 5 seconds), to derive the estimated median response spectrum.

From Figure 3-18, $S_a(0.13s) = 0.177g$ for both X and Y directions. The corresponding dispersion is 0.57.

Step 5. If the attenuation relationship does not include consideration of site characteristics and class, adjust the spectrum to account for these effects, using site response analysis, site class coefficients contained in ASCE/SEI 7 or other suitable adjustment factors.

Attenuation relationships generally return spectral acceleration values that reflect a geomean, \bar{S}_{gm} , of horizontal components (S_{ax} , S_{ay}), where:

$$\bar{S}_{gm} = \sqrt{S_{ax}S_{ay}}$$

Simplified analysis requires application of a spectral acceleration ordinate along each principal building axis. To convert the geomean spectrum to a pair of spectral ordinates oriented along each principal building axis, the process is as follows:

- Determine periods T_I^X and T_I^Y
- Using the response spectrum derived as described above, determine $S_a(T_I^X)$ and $S_a(T_I^Y)$

For simplified analysis both the value of spectral acceleration at the structure's effective first mode period, $S_a(0.13s)$, and the peak ground acceleration, $S_a(0s)$, are needed. These values can be obtained from the plot shown in Figure 3-18 or by reexecuting the *Attenuation Relationship Plotter* application for peak ground acceleration as an intensity measure in lieu of S_a .

For predictions of peak total floor velocity, a median estimate of the peak ground velocity is needed. The *Attenuation Relationship Plotter* application can be reexecuted to return median estimates and dispersions for this intensity measure in a fashion similar to that for peak ground acceleration.

3.4.2.2 Analyze Building Response

The objective of the analysis is to produce estimated median values of peak transient story drift ratios, peak floor accelerations, peak total floor velocities and residual drift. In general, the process is the same as that for intensity-based assessment. An adjustment to the process for assigning dispersion is needed, to incorporate the variability associated with the ground motion prediction, β_{gm} , which can be assigned from Table 3-10 or can be taken directly from the selected attenuation relationship.

3.4.2.2.1 Estimate Median Story Drift Ratio and Dispersion

Estimate the median story drift ratio according to Section 3.3.2.2.2. The equation to calculate story drift ratio dispersion, β_{SD} , is modified as follows:

$$\beta_{SD} = \sqrt{\beta_{aA}^2 + \beta_m^2 + \beta_{gm}^2}$$

where β_{gm} is the dispersion associated with the ground motion.

3.4.2.2.2 Estimate Median Peak Floor Acceleration and Dispersion

Estimate the median peak floor acceleration at each level according to Section 3.3.2.2.3. The equation to calculate floor acceleration dispersion, β_{FA} , is modified as follows:

$$\beta_{FA} = \sqrt{\beta_{aa}^2 + \beta_m^2 + \beta_{gm}^2}$$

where β_{gm} is the dispersion associated with the ground motion.

3.4.2.2.3 Estimate Median Peak Total Floor Velocity and Dispersion

Estimate the median peak floor velocity according to Section 3.3.2.2.4. The equation used to calculate floor velocity dispersion, β_{FV} , is modified as follows:

$$\beta_{FV} = \sqrt{\beta_{av}^2 + \beta_m^2 + \beta_{gm}^2}$$

where β_{gm} is the dispersion associated with the ground motion.

3.4.2.2.4 Estimate Median Residual Story Drift Ratio and Dispersion

Calculate the median residual story drift ratio according to Section 3.3.2.2.5. A value of 0.8 is to be used for the dispersion of residual story drift, β_{RD} , for intensity- or scenario-based assessments.

3.4.2.3 Input Response and Calculate Performance

Demand vectors and dispersions are organized and entered into PACT in a similar fashion as that described for intensity assessments in Section 3.3.2.3. Note that β_{gm} is incorporated into the total dispersion assigned to the median demand values. Figure 3-19 illustrates the **Structural Analysis Results** tab for the simplified analysis approach in scenario-based assessment.

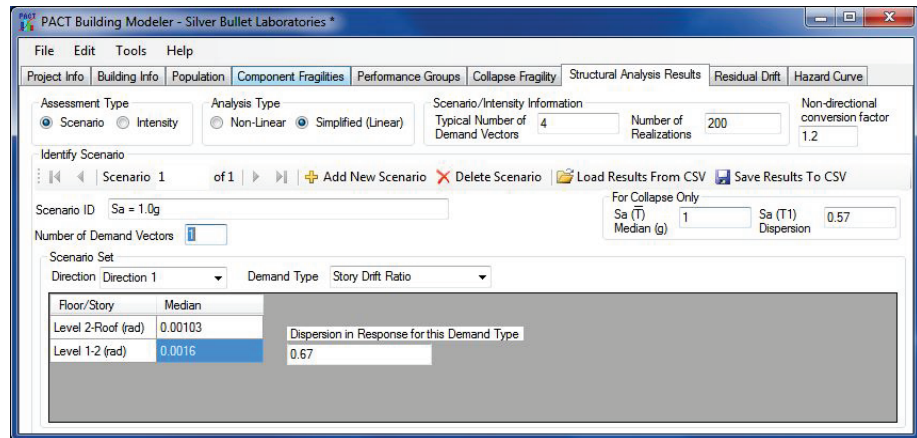


Figure 3-19 PACT Structural Analysis Results tab, scenario-based assessment, simplified analysis.

3.4.3 Review Results

The PACT assessment results for scenario-based assessment are similar to those produced for intensity-based assessment as illustrated in Section 3.3.

3.5 Time-Based Assessment

Time-based assessments express the probability of incurring impacts over a period of time, considering all earthquakes that occur in that time and the probability that they could occur. A site seismic hazard curve is used to express the annual frequency of exceedance for the values of a selected ground motion parameter. Ground motion parameters of interest for the assessment methodology include spectral acceleration at the average fundamental period of the building, peak ground acceleration, and peak ground velocity.

The time-based assessment process consists of a sequence of intensity-based assessments that span the range of potential seismic hazards from the lowest seismic intensity that can result in meaningful loss to the upper limits of intensity where total loss is highly probable. The process is performed by dividing the seismic hazard curve into a number of equal segments (eight segments are recommended). From each segment, a central value of spectral acceleration is selected and the building is analyzed for each intensity. The resulting curves express the annual frequency of exceedance for various performance measures. The sections that follow detail the steps in this process.

3.5.1 Nonlinear Response History Analysis

3.5.1.1 Define Earthquake Hazards

For time-based assessments, nonlinear response history analyses are conducted for m sets of n ground motion pairs each, scaled to appropriate intensity values using the procedures of Volume 1, Chapter 4. A value of 8 is recommended for m . For very weak buildings, m can be taken smaller than 8. For buildings with high resistance, it may be necessary to increase the number of segments or increase the range of segments to obtain stable results.

Ground motion records for time-based assessments are generated as follows:

Step 1. Determine the building's fundamental translational periods in two orthogonal directions (T_l^X and T_l^Y).

Step 2. Determine the average first mode period \bar{T} as the average of T_l^X and T_l^Y if the mode shapes are uncoupled and as the larger of T_l^X , and T_l^Y if the mode shapes are coupled.

Step 3. Generate a seismic hazard curve for the site for $S_a(\bar{T})$. This can be done by performing a site specific seismic hazard analysis or using hazard data compiled by the USGS.

Step 4. Define values of S_a^{min} and S_a^{max} that span the range of interest for the building.

$S_a^{min}(\bar{T})$ should reflect the onset of non-trivial impacts, and can be taken as follows:

$$S_a^{min} = 0.05g \text{ for } \bar{T} \leq 1.0s$$
$$S_a^{min} = \frac{0.05}{\bar{T}}g \text{ for } \bar{T} > 1.0s$$

S_a^{max} should reflect a maximum value for the selected performance measures, but need not exceed $\hat{S}_a(T)$, the building's median collapse capacity. Section 2.6 provides guidance on estimating median collapse capacity.

Step 5. Divide the seismic hazard curve into an appropriate number of intensity segments that span the range from S_a^{min} to S_a^{max} .

Step 6. For each segment defined in Step 5, identify the $S_{a_i}(\bar{T})$ value and the mean annual frequency of exceedance at the midpoint of the segment. Note that the difference between mean annual frequency of exceedance values at the segment ends defines the segment annual occurrence frequency $\Delta\lambda_i$.

Step 7. Develop an appropriate response spectrum for each of the $S_a(\bar{T})$ and λ_i value. Volume 1, Appendix B provides information on generation of various types of spectra. For events with a relatively large frequency, the uniform hazard and conditional mean spectra should have a similar shape and are both appropriate for use. For small frequency (infrequent) events, use of conditional mean or conditional spectra should improve estimates of drifts and accelerations over those generated using uniform hazard spectra.

Step 8. Select and scale ground motion pairs to the amplitude of the target spectrum at the $S_a(\bar{T})$ value similar to the process for intensity-based assessment. Ground motion record pairs can be found at: <https://ngawest2.berkeley.edu/> and www.cosmos-eq.org. A minimum of 7 record pairs with geomean spectral shape similar to the target spectrum should be used. If records with appropriate spectral shape cannot be found, at least 11 record pairs should be used.

Step 9. Repeat Step 8 for each hazard curve segment to obtain scaled records for the full range of the segments.

Section 3.5.2.1 illustrates Steps 1 through 6. Chapter 5 illustrates execution of Step 1 through Step 9 for a 4-story reinforced concrete frame structure.

3.5.1.2 Analyze Building Response

Analyze the structure with the selected records for each spectral intensity segment. Extract the peak transient drift ratios, floor accelerations, and peak total floor velocities for each of the orthogonal building directions. Calculate residual drift ratio and demand dispersions in the same manner as done for intensity-based assessment in Section 3.3.1.2.

For spectral intensities that approach the structure's median collapse capacity $\hat{S}_a(\bar{T})$, some ground motion pairs may produce predictions of collapse. Discard the results for analyses that produce collapse. In this case, additional analyses may be needed. Section 3.3.1.2 and Section 5.7 provide further guidance on this.

3.5.1.3 Input Response and Calculate Performance

For time-based assessments, PACT requires input of n demand vectors for each intensity assessment. Nonlinear response history analysis may produce a different number of demand vectors for each spectral segment due to occurrence of collapse for some records. Response vectors should include values for each demand parameter utilized by the selected component fragility specifications.

The structural analysis results for each intensity segment are input similarly. Information defining the mean annual frequency values of each intensity segment is input on the PACT **Hazard Curve** tab.

3.5.2 *Simplified Analysis*

3.5.2.1 **Define Earthquake Hazards**

Ground shaking effects are characterized by spectral ordinates extracted from a seismic hazard curve that spans the anticipated range of meaningful building response. Volume 1, Chapter 4 sets forth a procedure which is illustrated below.

The example uses the 2-story reinforced masonry wall structure previously defined.

Latitude: 37.98699

Longitude: -122.61644

$T_l^X = T_l^Y = 0.13$ seconds

Site Class: B

Step 1. Determine the fundamental translational periods in two orthogonal directions (T_l^X and T_l^Y).

$T_l^X = T_l^Y = 0.13$ seconds

Step 2. Determine the averaged first mode period \bar{T} as the average of T_l^X and T_l^Y if the mode shapes are uncoupled and as the larger of T_l^X and T_l^Y if the mode shapes are coupled.

$\bar{T} = 0.13$ seconds

Step 3. Define seismic hazard curve for site

The hazard curve can be constructed by using the following tools provided by the USGS: (1) the *Unified Hazard Tool* (<https://earthquake.usgs.gov/hazards/interactive/>); and (2) the *Java Ground Motion Parameter Calculator*. This example uses the *Java Calculator* to construct the hazard curve. The basic information necessary to generate the seismic hazard curve using this approach includes the site latitude and longitude (accurate to three decimal places), the average period, \bar{T} , and the site class.

The USGS application develops seismic hazard curves at the following discrete building periods: 0, 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 seconds. Figure 3-20 illustrates the spectral acceleration values at a period of 0.13 seconds interpolated from the USGS values and their corresponding mean annual frequency of exceedance. For a site class other than B, an adjustment of the spectral values is required.

Step 4. Define S_a^{min} and S_a^{max} that span the building's range of response interest. S_a^{min} should reflect the onset of non-trivial impacts, and for repair costs and repair time, can be taken as follows:

$$S_a^{min} = 0.05g \text{ for } \bar{T} \leq 1.0s$$

$$S_a^{min} = \frac{0.05}{\bar{T}} g \text{ for } \bar{T} > 1.0s$$

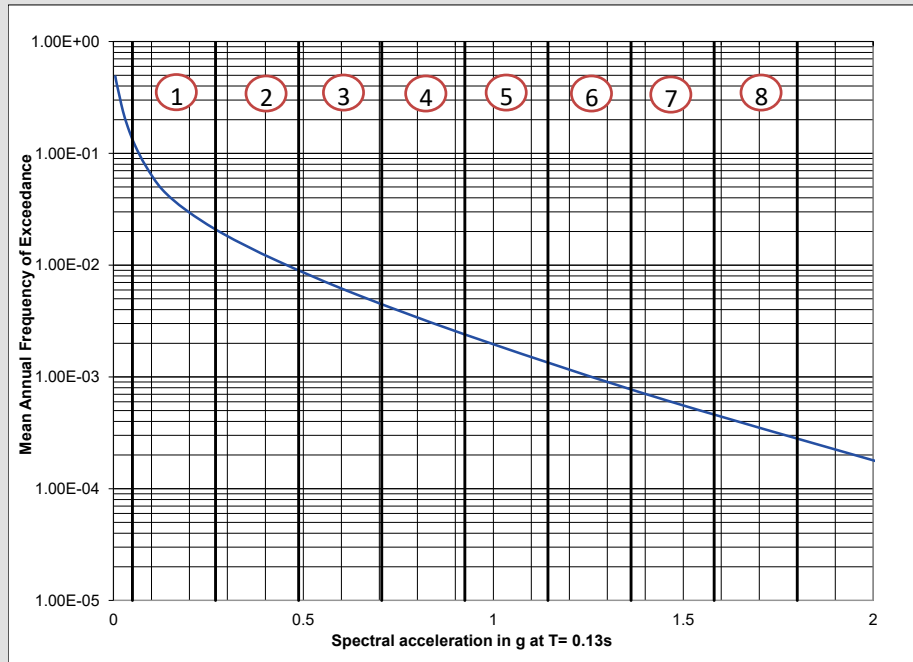


Figure 3-20 Seismic hazard plot showing segments.

Similarly, S_a^{max} should reflect demand that will produce a maximum value for the selected performance measures and can generally be taken as:

$$S_a^{max} = 2S_a(\bar{T})$$

where $S_a(\bar{T})$ is evaluated at a mean annual frequency of exceedance, λ , of 0.0004 but need not exceed $S_a(\bar{T})$, the building's median value of collapse fragility. Section 2.6 provides guidance on estimating building median collapse capacity.

For $\lambda = 0.0004$

$$S_a(\bar{T}) = 1.76g$$

$$2 \times S_a^{max} = 2 \times 1.76 = 3.52g > \hat{S}_a(\bar{T}) = 1.80g$$

Set $S_a^{max} = 1.80g$

Step 5. Divide the hazard curve into 8 equal segments:

For the $S_a(\bar{T})$ range of 0.05g to 1.80g, the spectral segment interval is

$$\frac{1.80 - 0.05}{8} = 0.21875 \text{ g}$$

Figure 3-20 illustrates the 8 equal width segments spanning from 0.05g to 1.80g.

Step 6. For each segment defined in Step 5, identify the $S_a(\bar{T})$ value at the segment midpoint and the associated mean annual frequency of exceedance, at each segment end, λ_i , λ_j , and midpoint, respectively. Hazard input into PACT uses segment midpoint $S_a(\bar{T})$ and λ values.

Table 3-10 summarizes the segment midpoint $S_a(\bar{T})$ values and associated mean annual frequency of exceedance values for each of the 8 spectral segments.

Table 3-10 Segmented Seismic Hazard Values

Segment	$S_a(\bar{T})$ at midpoint	λ_i	λ_j	λ at midpoint
1	0.1594	0.1372	0.0215	0.0395
2	0.3781	0.0215	0.0095	0.0139
3	0.5969	0.0095	0.0059	0.0067
4	0.8156	0.0059	0.0026	0.0037
5	1.0344	0.0026	0.0016	0.0019
6	1.2531	0.0016	0.0009	0.0012
7	1.4719	0.0009	0.0005	0.0006
8	1.6906	0.0005	0.0004	0.0005

Step 7. The peak ground acceleration hazard curve is obtained using the *Java Ground Motion Parameter Calculator*. This seismic hazard curve in Figure 3-21 expresses the variation in mean annual frequency of exceedance for peak ground acceleration (PGA).

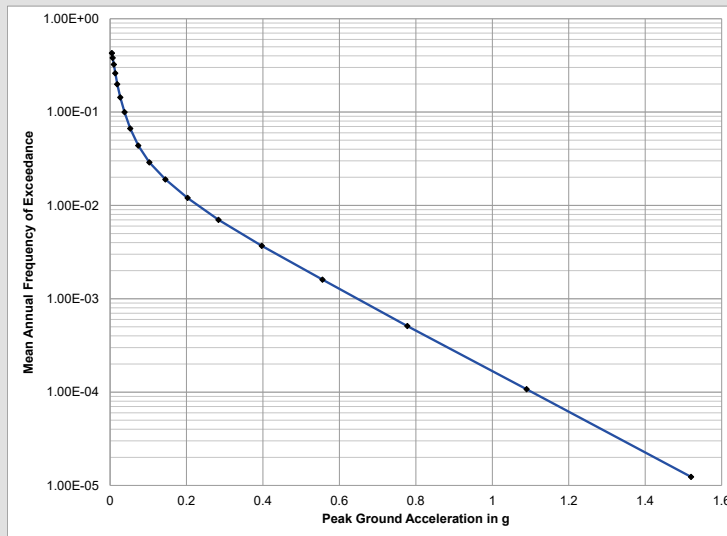


Figure 3-21 Variation of mean annual frequency of exceedance for peak ground acceleration in g.

Using the spectral segments defined in Table 3-10, Table 3-11 presents the corresponding mid-point peak ground acceleration values.

Table 3-11 Segmented Peak Ground Acceleration Values

Segment	<i>PGA</i>
1	0.029
2	0.134
3	0.244
4	0.322
5	0.481
6	0.559
7	0.696
8	0.774

3.5.2.2 Analyze Building Response

Analysis is performed for each intensity segment in the same fashion as for intensity-based assessment (See Section 3.3.2.2). The simplified analysis procedure is used to generate peak transient drifts, peak floor accelerations, peak total floor velocities, and residual drifts. The median demand estimates are assigned dispersions. Results include a vector of demands for each of the m intensity segments. The illustration below produces results for Segment 1. Median estimates for peak transient drift ratio, peak floor acceleration, peak total floor velocity and residual drift are calculated similarly for each spectral segment. The associated dispersions are similarly generated.

For Segment 1 as identified in Section 3.5.2.1:

$$S_a(\bar{T}) = 0.159g$$

$$PGA = 0.05g$$

$$\bar{T} = 0.13s, W = W_l = 1133k, V_{v_i} = 398 \text{ kips}$$

Step 1. Generate median story drift ratio estimates

According to Volume 1, Equation 5-6:

$$S = \frac{S_a(\bar{T})W}{V_{v_i}} = \frac{0.159(1133)}{398} = 0.45$$

Since $0.45 \leq 1.0$, according to Volume 1, Equation 5-7:

$$C_1 = 1.0$$

$$C_2 = 1.0$$

The load in each direction is computed using Volume 1, Equation 5-3:

$$V = C_1 C_2 S_a(\bar{T}) W_l$$

$$V = (1.0)(1.0)(0.159)(1133) = 180.1 \text{ kips}$$

Using the results presented in Section 3.3.2.2, the resulting structural displacements and drifts are scaled proportionately using the base shear ratio.

From previous analysis of the linear model:

$$V = 2226 \text{ kips}, \delta_r = 0.414 \text{ inches}, \delta_2 = 0.214 \text{ inches}$$

For Segment 1: $S_a = 0.159$,

$$\delta_r = \frac{180.1}{2226}(0.414) = 0.034 \text{ inches}$$

and

$$\delta_2 = \frac{180.1}{2226}(0.214) = 0.017$$

$$\Delta_1 = \frac{0.034}{(10)(12)} = 0.000283$$

$$\Delta_2 = \frac{0.034 - 0.017}{(10)(12)} = 0.000142$$

To obtain estimates of median story drift ratio, Δ_i^* , at each story by correcting for inelastic behavior and higher modes Volume 1, Equation 5-10 is used:

$$\Delta_i^* = H_{\Delta_i}(S, T_i, h_i, H) \times \Delta_i \quad i = 1 \text{ to } N$$

where $H_{\Delta_i}(S, T_i, h_i, H)$ is the drift modification factor for story i computed using Volume 1, Equation 5-11:

$$\ln(H_{\Delta_i}) = a_0 + a_1 T_i + a_2 S + a_3 \frac{h_{i+1}}{H} + a_4 \left(\frac{h_{i+1}}{H} \right)^2 + a_5 \left(\frac{h_{i+1}}{H} \right)^3, \quad S \geq 1, i = 1 \text{ to } N$$

with T_i , S , h_i and H as previously defined.

For a shear wall building of less than 10 stories tall, coefficients a_0 , a_1 , a_2 , a_3 , a_4 , and a_5 are determined from Volume 1, Table 5-4 as:

$$a_0 = 0.92, a_1 = -0.036, a_2 = -0.058, a_3 = -2.56, a_4 = 1.39, a_5 = 0$$

For $i = 1$, $h_2 = 10$ feet, $H = 20$ feet:

$$\ln H_{\Delta_1} = 0.92 - 0.036(0.13) - 0.058(0.45) - 2.56 \left(\frac{10}{20} \right) + 1.39 \left(\frac{10}{20} \right)^2$$

$$\ln H_{\Delta_1} = -0.043$$

$$H_{\Delta_1} = 0.957$$

$$\Delta_1^* = 0.957(0.000283) = 0.00027$$

For $i = 2$, $h_{roof} = H = 20$ feet

$$\ln H_{\Delta_2} = 0.92 - 0.036(0.13) - 0.058(0.45) - 2.56 \left(\frac{20}{20} \right) + 1.39 \left(\frac{20}{20} \right)^2$$

$$\ln H_{\Delta_2} = -0.281$$

$$H_{\Delta_2} = 0.755$$

$$\Delta_2^* = 0.755(0.000142) = 0.000107$$

From Table 3-4 for $T = 0.13$ seconds, $S = 0.45$:

$$\beta_{SD} = 0.26$$

Step 2. Generate median floor acceleration estimates

Obtain estimates of median peak floor acceleration, a_i^* , at each story above the building base by correcting peak ground accelerations using Volume 1, Equation 5-12:

$$a_i^* = H_{ai}(S, T, h_i, H) \times PGA \quad i = 2 \text{ to } N + 1$$

For this example, $PGA = 0.05g$.

H_{ai} is the acceleration correction factor for floor i given by Volume 1, Equation 5-13:

$$\ln(H_{ai}) = a_0 + a_1 T_l + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H} \right)^2 + a_5 \left(\frac{h_i}{H} \right)^3, \quad S \geq 1, \quad i = 2 \text{ to } N + 1$$

with T_l , S , h_i , and H as previously defined.

For a shear wall building of less than 10 stories tall, coefficients a_0 , a_1 , a_2 , a_3 , a_4 , and a_5 are found in Volume 1, Table 5-4 as:

$$a_0 = 0.66, a_1 = -0.15, a_2 = -0.084, a_3 = -0.26, a_4 = 0.57, a_5 = 0$$

For $i = 1$ (at grade):

$$a_1^* = pga = 0.05$$

For $i = 2$, $h_2 = 10 \text{ ft}$, $H = 20 \text{ ft}$

$$\ln H_{a_2} = 0.66 - 0.15(0.13) - 0.084(0.45) - 0.26 \left(\frac{10}{20} \right) + 0.57 \left(\frac{10}{20} \right)^2$$

$$\ln H_{a_2} = 0.6152$$

$$H_{a_2} = 1.85$$

$$a_2^* = 1.85(0.05) = 0.093g$$

For $i = 3$, $h_{roof} = H = 20 \text{ ft}$

$$\ln H_{a_3} = 0.66 - 0.15(0.13) - 0.084(0.45) - 0.26 \left(\frac{20}{20} \right) + 0.57 \left(\frac{20}{20} \right)^2$$

$$\ln H_{a_3} = 0.9127$$

$$H_{a_3} = 2.49$$

$$a_3^* = 2.49(0.05) = 0.125g$$

From Table 3-5 for $T = 0.13$ seconds, $S = 0.45$:

$$\beta_{FA} = 0.27$$

Step 3. Generate residual drifts.

From previous analysis:

$$\Delta_{2y} = 0.000283 > \Delta_2^* = 0.00027$$

$$\Delta_{1y} = 0.000142 > \Delta_1^* = 0.000107$$

Since peak transient drifts do not exceed the yield drifts, residual drift is zero for Segment 1.

3.5.2.3 Input Response and Calculate Performance

Analysis results are input into PACT in a manner similar to that for intensity-based assessments. The total number of intensity data sets should encompass all m hazard segments for all demand parameters in each principal building direction. Once the demand vectors are input, the hazard curve data are input into PACT using the **Hazard Curve** tab. The mean annual occurrence frequencies associated with each of the 8 spectral intensities are input. Figure 3-22 illustrates input of the spectral intensity information from Table 3-10 into PACT.

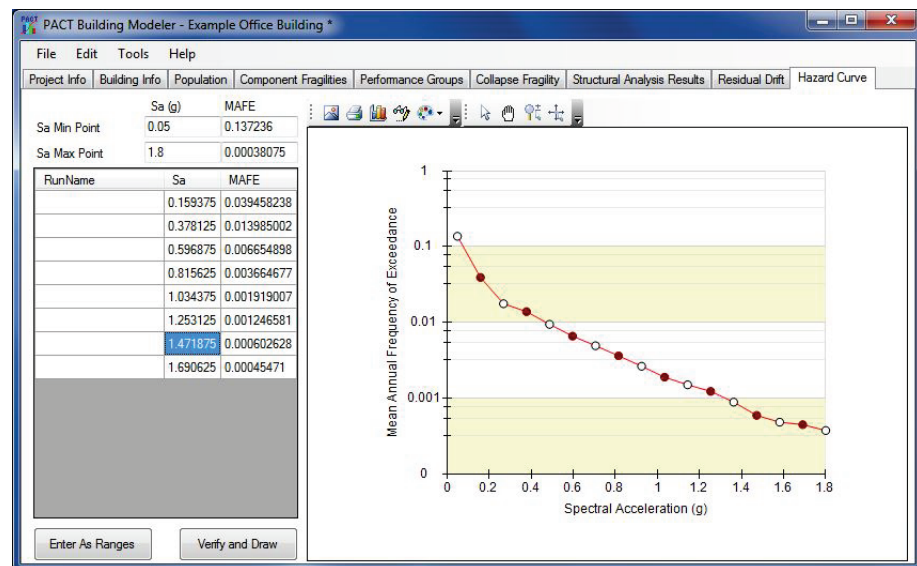


Figure 3-22 PACT Hazard Curve tab.

3.5.3 Review Results

PACT results for time-based assessments can be reviewed in terms of annual probabilities of non-exceedance for each performance measure. Chapter 5 illustrates sample results output for repair cost. Results can also be reviewed by intensity segment. For each intensity segment results can be reviewed in a similar fashion to those produced for intensity-based assessment as presented in Section 3.3.3.

Chapter 4

Example Application: Intensity-Based Performance Assessment Using Simplified Analysis

4.1 Introduction

This chapter provides an example application of the intensity-based performance assessment methodology using simplified analysis in the *Performance Assessment Calculation Tool* (PACT) with provided fragility and consequence function data.

The work necessary to obtain a median repair cost estimate for earthquake ground shaking with an average return period of 475 years (10% probability of exceedance in 50 years) for an office building is presented here as follows:

- Obtain site and building description (Section 4.2)
- Select assessment type and performance measure (Section 4.3)
- Assemble building performance model (Section 4.4)
- Select analysis method and construct analytical building model (Section 4.5)
- Define earthquake hazards (Section 4.6)
- Analyze building response (Section 4.7)
- Input response data and calculate performance (Section 4.8)
- Review results for selected performance measures (Section 4.9)

4.2 Obtain Site and Building Description

The building site for the example building is located in Los Angeles, California. The soil profile at the site is categorized as ASCE/SEI 7-10, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2010) Site Class D, having a shear wave velocity of 259 m/s in the upper 30 meters.

The structure has plan dimensions of 120 feet by 180 feet. Floor-to-floor height is 15 feet at the lower story and 13 feet at other stories. The structure

has reinforced concrete special moment frames around the building perimeter. The floors and roof are two-way post tensioned flat slabs (8 inches thick) supported by the perimeter moment frame and interior 18 inch square reinforced concrete columns on a 30 foot by 30 foot grid. Figure 4-1 and Figure 4-2 illustrate plan and elevation views. When entering into PACT, direction 1 is arbitrarily aligned with the North-South axis and direction 2 is aligned with the East-West building axis.

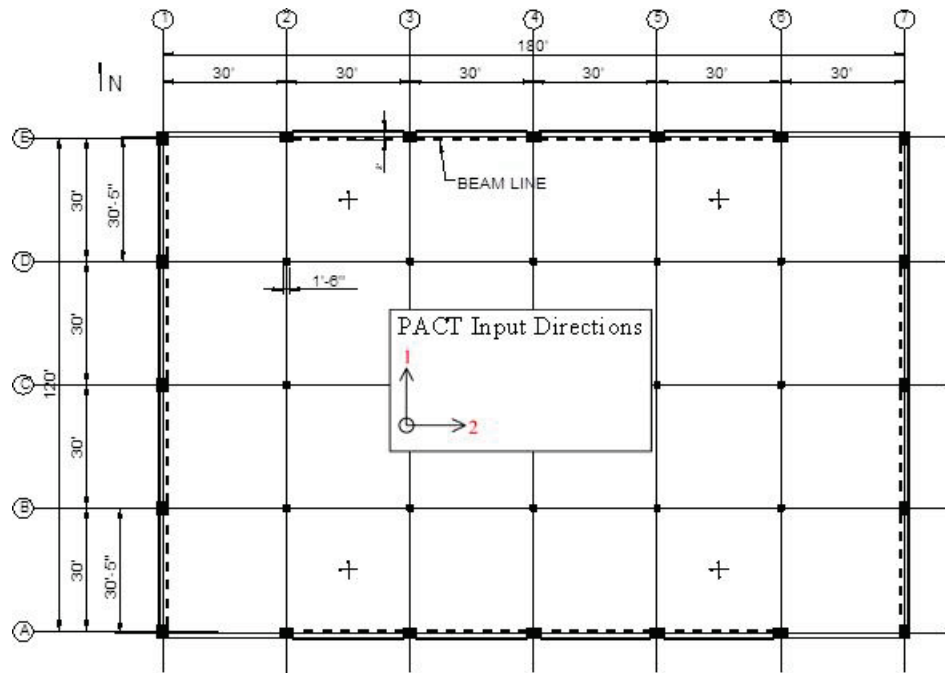


Figure 4-1 Plan view of example 4-story office building.

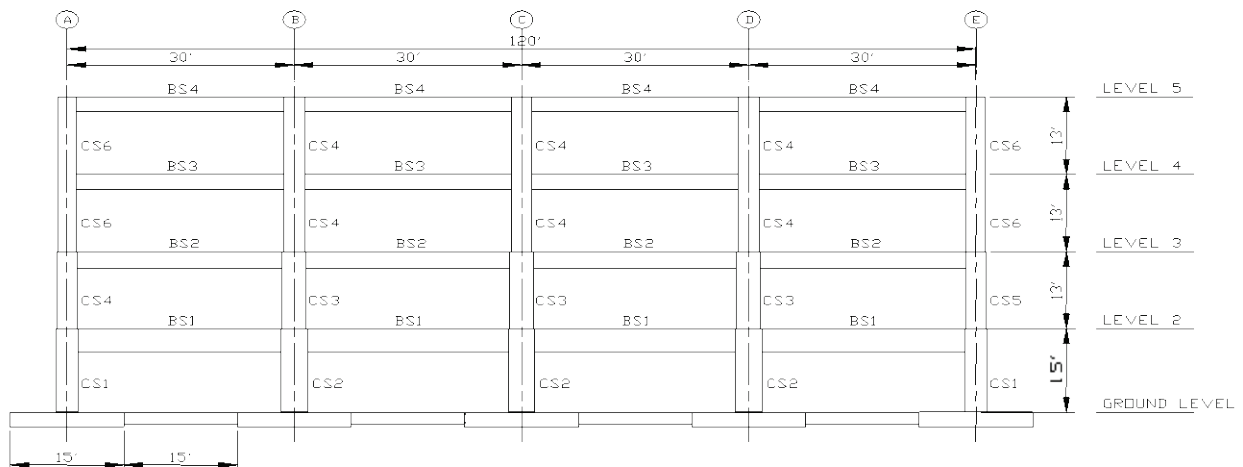


Figure 4-2 Typical frame elevation for example 4-story office building.

The building is designed and detailed according to the requirements of ASCE/SEI 7-05, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2005a), ACI 318-02, *Building Code Requirements for Structural Concrete and Commentary*, (ACI, 2002), and the 2007 *California Building Code* (ICC, 2007). Vulnerable nonstructural building features include exterior glazing, gypsum board partitions, suspended acoustical ceilings, fire sprinkler system, traction elevator, concrete roof tiles on a perimeter mansard, hot and cold water piping, and HVAC ducting. Tenant furnishings and equipment including office partitions and computers are not included in the assessment.

4.3 Select Assessment Type and Performance Measure

Intensity-based assessment will be performed with the building performance expressed in terms of repair costs as a percentage of total replacement cost.

4.4 Assemble Building Performance Model

The building performance model will be constructed in PACT by following the sequence:

1. Provide project information
2. Provide building characteristics
3. Select fragility specifications and performance groups
4. Identify collapse fragility and collapse modes
5. Provide residual drift fragility

The following subsections illustrate the implementation of this sequence.

4.4.1 Project Information

The first set of PACT data are input on the **Project Information** tab, as shown in Figure 4-3.

For this example, the regional and date cost multipliers are set equal to 1. For any particular building, these values should be set to reflect the actual building location and time value of escalation or devaluation effects. The PACT default consequence functions reflect 2011 costs for the Northern California region, which for this example, are deemed similar to those at the building's location in Southern California.

The **Solver Random Seed Value** is set to a non-zero value, 5, so that the assessment model will produce the same answer for multiple executions of the problem using the same input data.

Figure 4-3 PACT Project Information tab.

4.4.2 Building Information

At the top of the **Building Information** tab, the following information is input, as shown in Figure 4-4:

- **Number of Stories:** 4.
- **Total Replacement Cost:** Estimated as $\$250/\text{sf} \times 86,400 \text{ sf}$ or $\$21,600,000$.
- **Replacement Time:** Estimated as 550 days.
- **Core and Shell Replacement Cost:** Estimated as $\$100/\text{sf} \times 86,400 \text{ sf}$ or $\$8,460,000$.
- **Maximum Workers per Square Foot:** Default value of 0.001 is used.
- **Total Loss Threshold (as Ratio of Total Replacement Cost):** Default value of 1.0 is used.
- **Carbon Emissions Replacement (kg):** Estimated as: $[\$21,600,000 \text{ (total replacement cost)} \times 0.414 \text{ kg CO}_2\text{e}/\$ \text{ (environmental impact factor)}] / 0.88 \text{ (inflation factor from 2013 to 2011, based on U.S. Bureau of Economic Analysis)]$ or 10,161,818 kg CO₂e.
- **Embodied Energy Replacement (MJ):** Estimated as: $[\$21,600,000 \text{ (total replacement cost)} \times 5.729 \text{ MJ}/\$ \text{ (environmental impact factor)}] / 0.88 \text{ (inflation factor from 2013 to 2011, based on U.S. Bureau of Economic Analysis)]$ or 140,620,909 MJ.

In the **Most Typical Defaults** section, the following fields are input:

- **Floor Area:** 21,600 square feet
- **Floor Height:** 13 feet

Variation in floor height is input via the **Floor Number** drop down selector, which also permits input of non-typical floor areas.

Floor Num	Floor Name	Story Height (ft.)	Area (sq. ft.)	Height Factor	Hazmat Factor	Occupancy Factor
1	Floor 1	13.00	21,600.00	1	1	1
2	Floor 2	13.00	21,600.00	1	1	1
3	Floor 3	13.00	21,600.00	1	1	1
4	Floor 4	13.00	21,600.00	1	1	1
5	Floor 2		21,600.00	1	1	1

Figure 4-4 PACT Building Information tab.

The **Height Factor**, which adjusts repair cost and effort for the difficulty of performing work on upper floors of tall buildings, is set to 1 to reflect the lack of substantial cost differential for work performed on different floors of a low-rise building. Since the building is recently constructed, no lead-based paints or asbestos containing materials are present and thus the **Hazmat Factor** is set to 1. In this example, it is assumed that if the building is damaged, it can be vacated for repairs, so that increase of the cost and effort of repair in an occupied space is not expected, therefore, the **Occupancy Factor** is set equal to 1.

4.4.3 Population Distribution

Population distribution within the building is not an input required for the estimation of repair costs.

4.4.4 Structural Components

Fragility specifications provided in PACT are utilized for both structural and nonstructural components.

4.4.4.1 Structural Component Fragility Specifications

Structural components are input based on the basic building characteristics previously described. To input structural fragility groups, the dropdown

menu of selections in the **Component Fragilities** tab, shown in Figure 4-5, are utilized. These selections list the most typical specifications for the building and will be used by PACT to generate a floor-by-floor distribution of specifications. The selection process proceeds progressively from foundations through super structure. The following information summarizes the structural components included in the performance assessment model.

Most Typical Specifications

Category	Component	Dir. 1	Dir. 2	Population Model
B101: Floor Construction	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B102: Roof Construction	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B103: Structural Ste...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B104: Reinforced Co...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B1041.002a: ACI...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B1041.003b: ACI...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B1049.031: Post-...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B105: Masonry Verti...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B106: Cold-formed S...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	

Floor-by-Floor Distribution

of 5 (Floor 1)

Category	Component	Dir. 1	Dir. 2	Population Model
A202: Basement Walls	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B: Shell		<input type="checkbox"/>	<input type="checkbox"/>	
B10: Super Structure		<input type="checkbox"/>	<input type="checkbox"/>	
B101: Floor Construction	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B102: Roof Construction	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B103: Structural Ste...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B104: Reinforced Co...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B1041.002a: ACI...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B1041.003b: ACI...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B1049.031: Post-...		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Commercial Office
B105: Masonry Verti...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B106: Cold-formed S...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B107: Wood Light Fr...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	
B20: Exterior Enclosure		<input type="checkbox"/>	<input type="checkbox"/>	
B201: Exterior Nonst...	Please Select	<input type="checkbox"/>	<input type="checkbox"/>	

Figure 4-5 PACT input screen for beam/column joint fragility.

A10: Foundations. Foundations on this site will be considered rugged and thus not vulnerable to earthquake damage. No fragility group for foundations will be selected or input.

A20: Basement Construction. The example building has no basement. No fragility group is selected.

B10: Superstructure.

B101: Floor Construction. Elevated floors (8 inch post-tensioned flat slabs) will be considered rugged for in-plane (diaphragm) deformations. Vulnerability to slab-column joint rotations will be included under reinforced concrete elements (B104).

B102: Roof Construction. Roof construction (8 inch post-tensioned flat slabs) will be considered rugged for in-plane (diaphragm) behavior, similar

to the floor construction. Vulnerability to slab-column joint rotations will be included under reinforced concrete elements.

B104: Reinforced Concrete Elements. Appendix A provides a compilation of available structural fragility specifications for reinforced concrete moment frames. The following steps illustrate the selection of the appropriate fragility specifications for the example building:

- Selections range from classification number B1041.001a through B1049.133b, depending upon the framing system attributes.
- The building's primary lateral-force-resisting frames are detailed in accordance with a recent edition of ACI 318-02, *Building Code Requirements for Structural Concrete and Commentary*, (ACI, 2002). Therefore, the fragility specifications entitled "ACI 318 Special Moment Frames," ranging from B1041.001a through B1041.013b, are appropriate.
- Detailing is such that joint failure is not expected, and thus the selection range is narrowed to B1041.001a through B1041.003b. Beams occur on one side of the columns at grids A-1, A-2, A-6, A-7, E-1, E-2, E-6, and E-7 (fragility specifications B1041.001a, B1041.002a, and B1041.003a have beams on one side). Beams occur on two sides of the columns at grids A-3, A-4, A-5, B-1, B-7, C-1, C-7, D-1, D-7, E-3, E-4, and E-5 (fragility specifications B1041.001b, B1041.002b, and B1041.003b have beams on both sides).
- Beam sizes for all framing bays are 34 inches wide by 30 inches deep. As noted in Section 2.4.2, special moment frame fragility specifications with varying beams sizes are provided (B1041.001 for 24×24, B1041.002 for 24×36, and B1041.003 for 36×36).

Based on the criteria listed above, a reasonable selection of fragility specifications to estimate the consequences for four 34×30 inch beams in the example building is illustrated in Figure 4-6 and listed as the following:

- B1041.002a for the one-sided beam/column joints with a 24×36 inch size beam
- B1041.003b for the beam/column joints with 36×36 inch beams framing into the column from each side

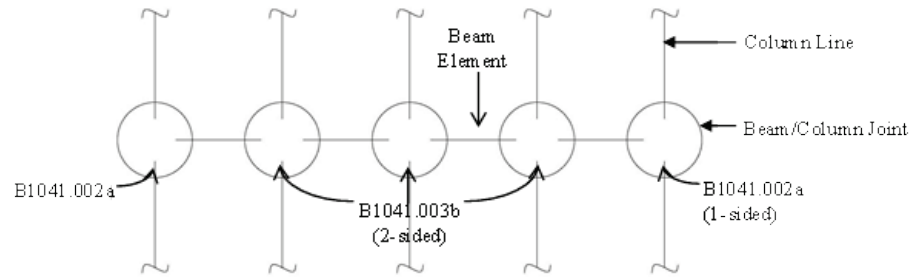


Figure 4-6 Illustration of reinforced concrete element fragility specification selections.

Although users can modify the provided fragility specification to reflect the actual 34×30 inch beam size, this level of precision is typically not justified. Table 4-1 summarizes the fragility group selections.

Table 4-1 Fragility Group Selections for the Beam/Column Components

Joint Location	Fragility Classification Number	Input Direction	Joint Location	Fragility Classification Number	Input Direction
A-1	B1041.002a	1	A-5	B1041.003b	2
A-2	B1041.002a	2	B-1	B1041.003b	1
A-6	B1041.002a	2	B-7	B1041.003b	1
A-7	B1041.002a	1	C-1	B1041.003b	1
E-1	B1041.002a	1	C-7	B1041.003b	1
E-2	B1041.002a	2	D-1	B1041.003b	1
E-6	B1041.002a	2	D-7	B1041.003b	1
E-7	B1041.002a	1	E-3	B1041.003b	2
A-3	B1041.003b	2	E-4	B1041.003b	2
A-4	B1041.003b	2	E-5	B1041.003b	2

Other vulnerable reinforced concrete elements include the post-tensioned slab-column joints. Post-tensioned reinforced concrete slab systems are listed as fragility groups B1049.021a through B1049.032. In the example building, slab shear reinforcement has been provided at columns and the gravity shear to shear capacity ratio is less than 0.4. Thus, B1049.031 is the most appropriate selection. This fragility specification is defined with a non-directional demand parameter since the joints are subject to damage when story drifts occur in any direction. As shown in Figure 4-5, the non-directional fragility is signified by a solid block in the columns for direction 1 and direction 2, compared to a check mark symbol for a directional fragility.

Figure 4-5 illustrates selection of the above fragility groups in the upper half of the **Component Fragilities** tab. The lower half of Figure 4-5 illustrates

the fragility groups selected for the first floor. The user must edit this half of the window to indicate the fragility specifications that apply at each floor and for each direction. If components identified in the upper half of the page do not occur on all floors or in both directions, they should be deleted from the floors where they do not occur, on the bottom half of the page.

4.4.4.2 Structural Component Performance Groups

Quantities are assigned and distributed among the building floors using the **Performance Groups** tab. This tab will be imprinted with the previously selected structural fragility specifications on the **Component Fragilities** tab.

For each floor, the number of special moment frame beam-column joints vulnerable to story drift in each building direction are entered for each of the pre-selected specifications. Table 4-2 reorganizes Table 4-1 for use in defining performance groups in PACT:

Table 4-2 Performance Group Quantities for Reinforced Concrete Elements

Fragility Classification Number	Direction	Number Per Floor
B1041.002a	1	4
B1041.002a	2	4
B1041.003b	1	6
B1041.003b	2	6

Note that for these components, no dispersion is identified with the quantity since it is known precisely. Note also that for this example, components within the performance group are designated as correlated. With this option selected, PACT will execute realizations for the entire group and assign a damage state distribution among the members of the group that reflect the result of the realization. If the components are designated as uncorrelated, PACT will determine unique damage states for each component within the group for each realization. Since only a median estimate of loss is desired in this example, the assumption of fragility correlation is appropriate. If statistics on the possible range of loss are desired, or the probability of obtaining an unsafe placard is needed, the component performance groups should be designated as being uncorrelated.

Input of the post-tensioned slab/column joint information is similarly inserted at each floor; however, these fragilities are input as non-directional. There are 15 joints per floor.

The performance group definition process is repeated for each floor and for each direction (including non-directional). Figure 4-7 through Figure 4-9

illustrate data input for direction 1, direction 2, and non-directional fragility specifications on the first floor.

The screenshot shows the 'Performance Groups' tab in the PACT Building Modeler software. The 'Direction' section has 'Direction 1' selected. The table below lists performance groups for floor 1 of 5 floors.

No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1041.002a	ACI 318 SMF, Conc Col & Bm = 24" x 36", Beam one ...	4.00	0.00	<input checked="" type="checkbox"/>	Commercial Office	Story Drift Ratio
B1041.003b	ACI 318 SMF, Conc Col & Bm = 36" x 36", Beam both ...	6.00	0.00	<input checked="" type="checkbox"/>	Commercial Office	Story Drift Ratio

Figure 4-7 PACT entries for 1st floor structural performance groups, direction 1.

The screenshot shows the 'Performance Groups' tab in the PACT Building Modeler software. The 'Direction' section has 'Direction 2' selected. The table below lists performance groups for floor 1 of 5 floors.

No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1041.002a	ACI 318 SMF, Conc Col & Bm = 24" x 36", Beam one ...	4.00	0.00	<input checked="" type="checkbox"/>	Commercial Office	Story Drift Ratio
B1041.003b	ACI 318 SMF, Conc Col & Bm = 36" x 36", Beam both ...	6.00	0.00	<input checked="" type="checkbox"/>	Commercial Office	Story Drift Ratio

Figure 4-8 PACT entries for 1st floor structural performance groups, direction 2.

The screenshot shows the 'Performance Groups' tab in the PACT Building Modeler software. The 'Direction' section has 'Non-Directional' selected. The table below lists performance groups for floor 1 of 5 floors.

No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1049.031	Post-tensioned concrete flat slabs- columns with shear ...	15.00	0.00	<input checked="" type="checkbox"/>	Commercial Office	Story Drift Ratio

Figure 4-9 PACT entries for 1st floor structural performance groups, non-directional.

4.4.5 Nonstructural Components

4.4.5.1 Nonstructural Component Fragility Specifications

The process of identifying and selecting the type and distribution of the nonstructural components can be greatly simplified by the use of the *Normative Quantity Estimation Tool*, provided in Volume 3. This tool can be used to generate a floor-by-floor listing of nonstructural components with estimates of their performance group quantities with the simple input of building floor areas and occupancies. The tool is an aid for estimating normative quantities and careful review by the user is necessary. Also note that the tool only identifies typical quantities of components present in a building without distinguishing their vulnerability to damage. For example,

the tool will identify the typical square footage of suspended ceilings in a building without discrimination as to the extent of seismic bracing present. Users must determine this aspect of performance group selection by themselves.

To use the *Normative Quantity Estimation Tool*, the building floors and occupancies are entered into the **Building Definition Table** in the **Normative Quantity Estimation** tab. Figure 4-10 illustrates input of this information for the example building.

4	N floors	5								
5										
6	BUILDING DEFINITION TABLE									
7	Floor Name	Floor #	Total Floor Area	Occupancy		Occupancy 2		Occupancy 3		SUM % AREA
8			(sf)	Type	% Area	Type	% Area	Type	% Area	
9										
10	Roof	5	21600	none	100%	none	0%	none	0%	100%
11	4th	4	21600	OFFICE	100%	none	0%	none	0%	100%
12	3rd	3	21600	OFFICE	100%	none	0%	none	0%	100%
13	2nd	2	21600	OFFICE	100%	none	0%	none	0%	100%
14	1st	1	21600	OFFICE	100%	none	0%	none	0%	100%
15										
16										
17										
18										

Figure 4-10 Normative Quantity Estimation Tool, Building Definition Table.

After this information is entered, pressing the **Compile** button at the top of the worksheet executes the tool and produces a list of nonstructural components and their representative quantity at each floor for each occupancy type. Figure 4-11 shows inventory generated for floor 3 of the example building. Similar information is also generated for other levels.

The nonstructural components listed in Figure 4-11 represent the most probable distribution found in typical buildings with commercial office occupancy and having the same size as the building under evaluation. This distribution is based on expert judgment. Every building will have somewhat different types and quantities of components than those identified by the tool and this will also vary over time. If desired, a building specific inventory can be performed to capture a more accurate distribution of these nonstructural components at the time the evaluation is performed.

A median estimate of the number of units is provided for each fragility specification listed in Figure 4-11. The total number of units is identified for both directional and non-directional specifications. The user must distribute the total number of directional units between direction 1 and direction 2. It should be noted that for distributed systems, such as piping or partitions, units of measure for components are typically hundreds of lineal or square feet. As a result, the quantity of units calculated will often be a decimal fraction. If it is assumed that the fragility of all components within a

performance group is correlated, these decimal fractions can be used directly. However, if uncorrelated behavior is assumed, the units should be entered as integers.

	N	O	P	Q	R	S	T	U	V
1	Compile		Processing of Incomplete Data		Processing of Zero Data		Sum Fragility by Floor		
2			<input checked="" type="radio"/> Ignore Incomplete Data	<input checked="" type="radio"/> Exclude Zero Data	<input checked="" type="radio"/> List as Zero	<input checked="" type="radio"/> Sum Components by Building & Floor			
3			<input type="radio"/> Include Incomplete Data	<input type="radio"/> Include Zero Data	<input type="radio"/> "Not Typically Included"	<input type="radio"/> Sum Components by Floor			
4					<input type="radio"/> List All Components				
5									
6	COMPONENT SUMMARY MATRIX								
7	OCCUPANCY				Fragility Number	Fragility Name	Assumed Quantity per component within PACT	Quantity	
8	Type	Occupancy #	Floor Name	Component Area (sq ft)				Directional	Non Directional
9									
44	OFFICE	1	3rd	21600	B2022.001	B2022.001 Curtain Walls - Generic Midrise Stick-Built Cur	30 SF	216.00	--
45	OFFICE	1	3rd	21600	B3011.011	B3011.011 Concrete tile roof, tiles secured and complian	100 SF	--	58.32
46	OFFICE	1	3rd	21600	C1011.001a	C1011.001a Wall Partition, Type: Gypsum with metal stud	100 LF	21.60	--
47	OFFICE	1	3rd	21600	C3011.002c	C3011.002c Wall Partition, Type: Gypsum + Ceramic Tile,	100 LF	1.63	--
48	OFFICE	1	3rd	21600	C3032.003b	C3032.003b Suspended Ceiling, SDC D,E (Ip=1.0), Area (A)	600 SF	--	32.40
49	OFFICE	1	3rd	21600	C3034.002	C3034.002 Independent Pendant Lighting - seismically ra	1 EA	--	324.00
50	OFFICE	1	3rd	21600	D2021.013a	D2021.013a Cold Water Piping (dia > 2.5 inches), SDC D,E	1000 LF	--	0.32
51	OFFICE	1	3rd	21600	D2022.013a	D2022.013a Hot Water Piping - Small Diameter Threaded	1000 LF	--	1.81
52	OFFICE	1	3rd	21600	D2022.023a	D2022.023a Hot Water Piping - Large Diameter Welded S	1000 LF	--	0.65
53	OFFICE	1	3rd	21600	D2031.013b	D2031.013b Sanitary Waste Piping - Cast Iron w/flexible c	1000 LF	--	1.23
54	OFFICE	1	3rd	21600	D3041.021c	D3041.021c HVAC Stainless Steel Ducting less than 6 sq. f	1000 LF	--	0.43
55	OFFICE	1	3rd	21600	D3041.032c	D3041.032c HVAC Drops / Diffusers without ceilings - sup	10 EA	--	19.44
56	OFFICE	1	3rd	21600	D3041.041b	D3041.041b Variable Air Volume (VAV) box with in-line c	10 EA	--	10.80
57	OFFICE	1	3rd	21600	D4011.033a	D4011.033a Fire Sprinkler Drop Standard Threaded Steel	100 EA	--	1.94
58	OFFICE	1	3rd	21600	E2022.001	E2022.001 Modular office work stations.	1 EA	--	151.20
59	OFFICE	1	3rd	21600	E2022.102a	E2022.102a Bookcase, 2 shelves, unanchored laterally	1 EA	--	43.20
60	OFFICE	1	3rd	21600	E2022.112a	E2022.112a Vertical Filing Cabinet, 2 drawer, unanchored	1 EA	--	17.28

Figure 4-11 Normative Quantity Estimation tool, Component Summary Matrix showing nonstructural inventory.

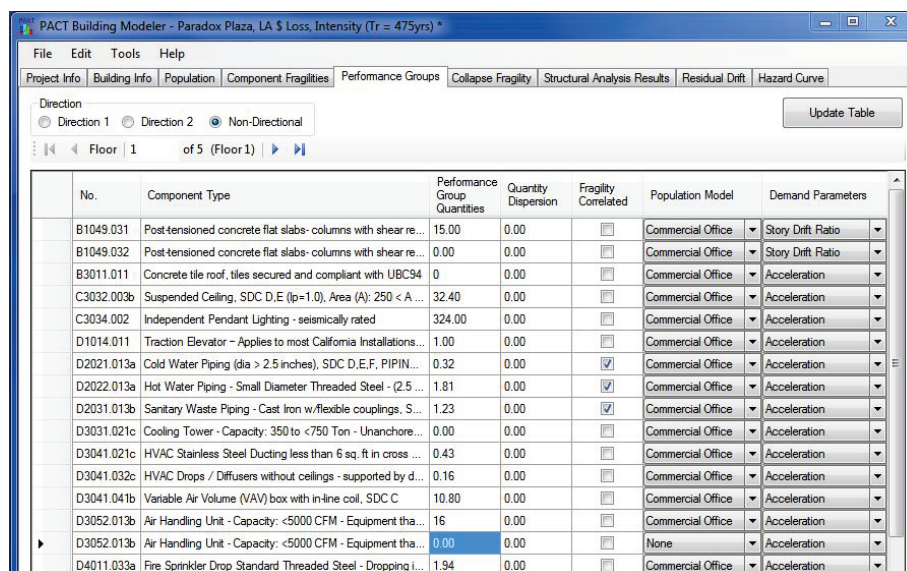
Similar to the structural fragility specifications, the user must transfer this information onto the **Component Fragilities** and **Performance Groups** tabs in PACT. The user should review the fragility specifications and quantities provided by the *Normative Quantity Estimation Tool* for their appropriateness at each floor and modify quantities and add (or delete) fragility selections as appropriate to best reflect the damageable nonstructural components present at each floor. Items that occur only once in the building are kept at the appropriate floor and deleted from other floors. For example, roof tiles only occur at the roof level.

4.4.5.2 Nonstructural Component Performance Groups

After completion of the floor-by-floor input of fragility specification data, nonstructural performance groups can be identified and input using the **Performance Groups** tab. When the tab is initiated PACT will provide a warning at the bottom of the window if fragility groups that require user-defined information, such as anchorage capacity, are selected. Figure 4-12 illustrates PACT input of first floor data for non-directional performance groups respectively.

The performance group quantities identified with the *Normative Quantity Estimation Tool* are median estimates. For distributed systems (piping, ducting, ceilings, etc.), the median estimates are accompanied by dispersions that reflect the variability in component quantity for the selected occupancy.

For this example, the dispersion input to PACT has been set to 0 to reflect a precise understanding of the amounts of components. In most instances, the user should select the recommended dispersion values from the tool to reflect the variability of the component, both as presently deployed and as may be modified over time. If the user is confident in the quantity of the component, the dispersion can be set to 0. For discrete items such as boilers and cooling towers, a dispersion value of 0 will generally be a more appropriate selection since the quantity of these components varies by whole integers and the *Normative Quantity Estimation Tool* will round off its median estimate to the nearest whole integer.



No.	Component Type	Performance Group Quantities	Quantity Dispersion	Fragility Correlated	Population Model	Demand Parameters
B1049.031	Post-tensioned concrete flat slabs - columns with shear re...	15.00	0.00	<input type="checkbox"/>	Commercial Office	Story Drift Ratio
B1049.032	Post-tensioned concrete flat slabs - columns with shear re...	0.00	0.00	<input type="checkbox"/>	Commercial Office	Story Drift Ratio
B3011.011	Concrete tile roof, tiles secured and compliant with UBC94	0	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
C3032.003b	Suspended Ceiling, SDC D,E (Ip=1.0), Area (A): 250 < A ...	32.40	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
C3034.002	Independent Pendant Lighting - seismically rated	324.00	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D1014.011	Traction Elevator - Applies to most California Installations...	1.00	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D2021.013a	Cold Water Piping (dia > 2.5 inches), SDC D,E,F, PIPIN...	0.32	0.00	<input checked="" type="checkbox"/>	Commercial Office	Acceleration
D2022.013a	Hot Water Piping - Small Diameter Threaded Steel - (2.5 ...	1.81	0.00	<input checked="" type="checkbox"/>	Commercial Office	Acceleration
D2031.013b	Sanitary Waste Piping - Cast Iron w/flexible couplings, S...	1.23	0.00	<input checked="" type="checkbox"/>	Commercial Office	Acceleration
D3031.021c	Cooling Tower - Capacity: 350 to <750 Ton - Unanchore...	0.00	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D3041.021c	HVAC Stainless Steel Ducting less than 6 sq. ft in cross ...	0.43	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D3041.032c	HVAC Drops / Diffusers without ceilings - supported by d...	0.16	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D3041.041b	Variable Air Volume (VAV) box with in-line coil, SDC C	10.80	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D3052.013b	Air Handling Unit - Capacity: <5000 CFM - Equipment tha...	16	0.00	<input type="checkbox"/>	Commercial Office	Acceleration
D3052.013b	Air Handling Unit - Capacity: <5000 CFM - Equipment tha...	0.00	0.00	<input type="checkbox"/>	None	Acceleration
D4011.033a	Fire Sprinkler Drop Standard Threaded Steel - Dropping i...	1.94	0.00	<input type="checkbox"/>	Commercial Office	Acceleration

Figure 4-12 PACT Performance Groups tab for floor 1, non-directional.

The following information summarizes the nonstructural components included in the performance assessment model based on the results obtained from the *Normative Quantity Estimation Tool*. The normative and actual quantities are not rounded for illustration purposes.

B20: Exterior Enclosure

B201: Exterior Nonstructural Walls. The building's exterior skin is a glazed curtain wall consisting of glazing (category B202) and aluminum panels. The aluminum panels are considered rugged and therefore no fragility group is selected.

B202: Exterior Windows. The building includes 5 foot by 6 foot panels (6:5 aspect ratio) of insulated single pane annealed insulated glazing units with no additional information. According to guidance provided in Section 2.5.2 and Table B-2, these components are identified as B2022.001. The *Normative Quantity Estimation Tool* indicates that 216 units of 30 square foot of glazing will be present on each floor of this building in total, in both directions. Since each panel is 5 foot by 6 foot in size, this corresponds to 216 panels. Based on the building dimensions given in Figure 4-1, the glazing quantities can be distributed in a 2 to 3 ratio between direction 1 and direction 2.

B203: Exterior Doors. Exterior doors are considered to be rugged items for the subject structure. No fragility group is selected.

B30: Roofing

B301: Roof Coverings. The subject structure has a system of concrete roof tiles attached to the mansard roof in compliance with the 2007 *California Building Code*. For this assessment, the attachment is deemed similar to the requirements of the 1994 UBC, *Uniform Building Code*, (ICC, 1994). Accordingly, specification B3011.011 best defines the roof system damageability.

C10: Interior Construction

C101: Partitions. Interior partitions consist of gypsum wallboard over steel studs that are fixed at top and bottom. Fragility specification C1011.001a is selected to best characterize the performance of the building partitions. Wall finishes are identified under category C301 below.

C20: Stairs

The specification that describes prefabricated steel stairs with seismic joints, C1011.001, is selected. The *Normative Quantity Estimation Tool* indicates a quantity of 3 stairs within the building. Each stair is oriented in direction 1.

C30: Interior Finishes

C301: Wall Finishes. Ceramic tile finish has been included (C3011.002c) at each floor of the building. Finish on partition walls are measured in units of 100 lineal feet, with an estimated height of 9 feet. The *Normative Quantity Estimation Tool* indicates a quantity of 1.63 units (163 lineal feet) in total for directions 1 and 2.

C303: Ceilings. The structure has suspended acoustical ceilings, C3032.003b. The *Normative Quantity Estimation Tool* indicates that 32.40

units of suspended ceilings, measured in units of 600 square feet, will be present. This fragility is identified as non-directional.

Specification C3034.002 is selected for suspended pendulum lighting with independent support wires. The *Normative Quantity Estimation Tool* estimates that 324 units are present per floor for this non-directional specification.

D10: Conveying

D101: Elevators and Lifts. The structure includes one traction elevator, D1014.011. This non-directional component is located only at floor 1.

D20: Plumbing

Table 4-3 summarizes the selection of plumbing components and quantities indicated by the *Normative Quantity Estimation Tool*.

Table 4-3 Performance Group Quantities for Plumbing Components

General Description	Fragility ID	Quantity per Floor	Unit of Measure	Actual Quantity
Domestic Cold Water Piping – (greater than 2 ½ Φ)	D2021.013a	0.32	1000 LF	324 feet
Domestic Hot Water Piping – (less than 2 ½ inch Φ)	D2022.013a	1.81	1000 LF	1814.4 feet
Domestic Hot Water Piping – (greater than 2 ½ inch Φ)	D2022.023a	0.65	1000 LF	648 feet
Sanitary Waste Piping, Cast Iron with Flexible Couplings	D2031.013b	1.23	1000 LF	1231.2 feet

D30: HVAC

D304: HVAC Distribution Systems. This category includes fans, drops, diffusers, and variable air volume (VAV) boxes. Table 4-4 summarizes the selection of HVAC distribution components, system fragility specifications and performance groups indicated using the *Normative Quantity Estimation Tool*.

D306: Packaged Air Handling Units. The *Normative Quantity Estimation Tool* recommends 16 units of D3052.013b with a capacity of 4,000 CF each. These units are non-directional and located in the first floor.

Table 4-4 Performance Group Quantities for Distributed HVAC Components

General Description	Fragility ID	Quantity per Floor	Unit of Measure	Actual Quantity
HVAC stainless ducting < 6 ft. ²	D3041.021c	0.43	1000 LF	432 feet
HVAC drops/diffusers without ceilings	D3041.032c	19.44	10 each	194.4
Variable Air Volume boxes	D3041.041b	10.8	10 each	108

D40: Fire Protection

D401: Fire Sprinkler. Fragility specification D4011.033a was selected to represent suppression sprinklers dropping into unbraced soft lay-in tile ceilings. It is further assumed that since the building is of recent construction, the ceiling bracing conforms to Seismic Design Category D, E, or F to appropriately reflect the seismic hazard of the Los Angeles site. The fragility specification for D4011.033a identifies the units of measure for fire sprinkler drops as 100 each. The *Normative Quantity Estimation Tool* indicates 1.94 units, thus 194 drops at each floor.

D50: Electrical

The fragility specification D5012.023d was selected for low voltage switchgear with a unit of measure of 400 amps. The *Normative Quantity Estimation Tool* indicates one unit per floor is present.

Equipment and furnishings and fragilities for special construction were not considered.

4.4.6 Collapse Fragility and Collapse Modes**4.4.6.1 Collapse Fragility**

Volume 1, Chapter 6 discusses three approaches for development of collapse fragility. This example demonstrates the use of the nonlinear static approach as summarized in Section 2.6.2.

Step 1. Construct a mathematical model of the building for nonlinear static analysis in each building direction. For the example structure, each building direction has identical strength and stiffness characteristics so only one analysis is needed.

Step 2. Nonlinear static analysis was performed to identify the sequence of component yielding to a deformation at which collapse is judged to occur.

Step 3. Figure 4-13 illustrates the results of the pushover analysis for both building direction 1 and direction 2, which are identical. Collapse is judged

to occur at a roof drift of 2.7 feet, which corresponds to a roof drift ratio of 5%.

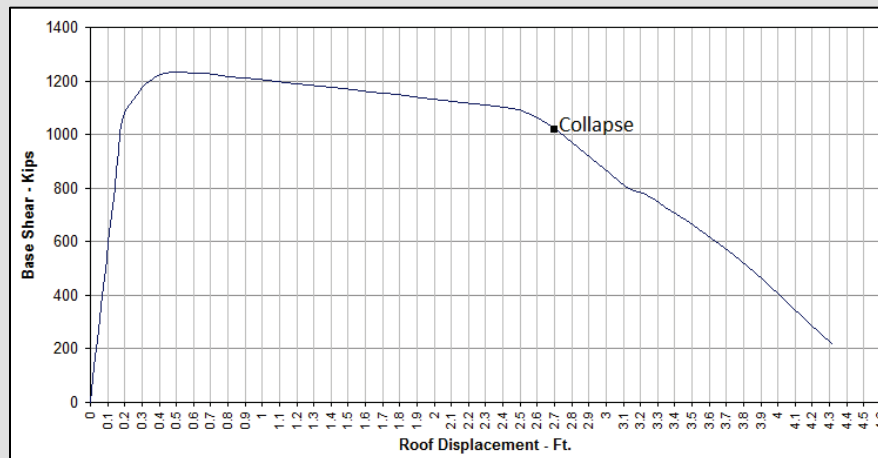


Figure 4-13 Pushover curve developed by analysis.

Step 4. The coordinates of the pushover curve in Figure 4-15 are input into the *SPO2IDA Tool* provided in Volume 3 along with the building height (54 feet), building weight (8365.6 kips) and fundamental building period (1.13seconds). Four control points are used to approximate the pushover curve as illustrated in Figure 4-14.

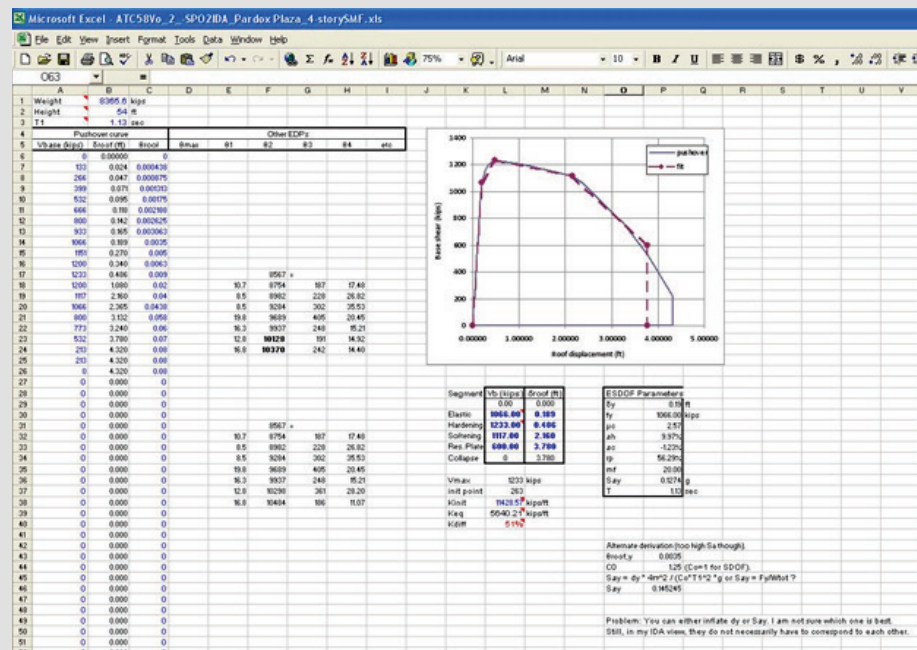


Figure 4-14 SPO2IDA Tool, SPO tab.

Step 5. Figure 4-15 presents the results of the SPO2IDA evaluation. The value of $\hat{S}_a(\bar{T})$ is estimated as 2.23g. The collapse fragility is thus defined as having a median value $\hat{S}_a(\bar{T})$ of 2.23g and a dispersion of 0.6.

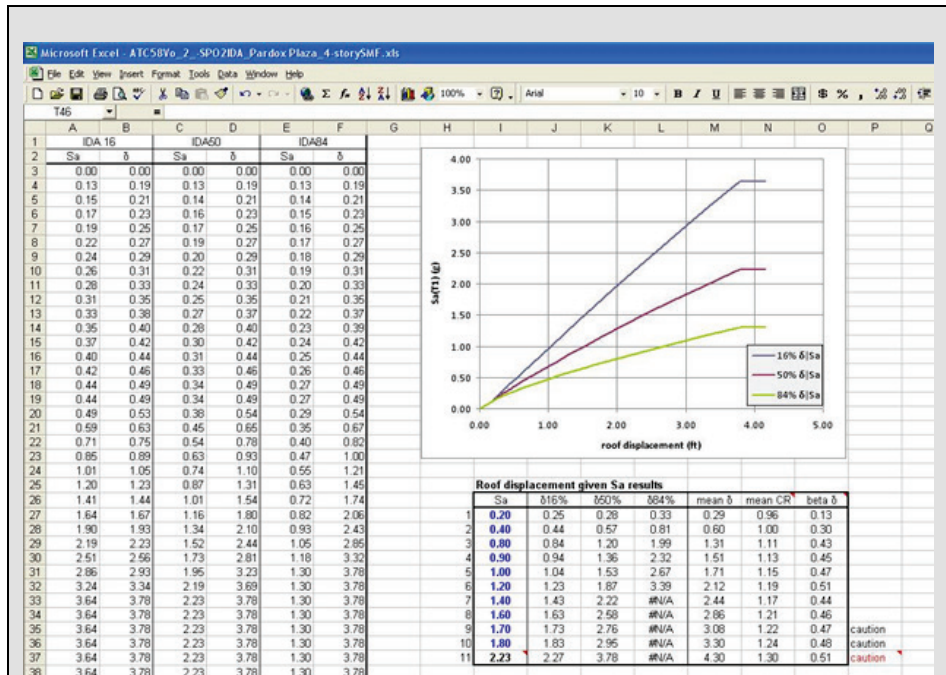


Figure 4-15 SPO2IDA Tool, IDA Results tab.

Step 6. The median collapse capacity and a dispersion of 0.6 are input into PACT using the **Collapse Fragility** tab, as shown in Figure 4-16.

Include Potential Collapse in Assessment

Collapse Fragility In terms of $S_a(T)$ Median: 2.23 Dispersion: 0.6

Number of Potential Collapse Modes: 1

Mutually Exclusive Probability of Mode Given Collapse

Floor	Mode 1
Floor 4 (4)	1
Floor 3 (3)	1
Floor 2 (2)	1
Floor 1 (1)	1

Fraction of Floor Subject to Collapse Debris

Floor	Mode 1
Floor 4 (4)	1
Floor 3 (3)	1
Floor 2 (2)	1
Floor 1 (1)	1

Collapse Consequences

Floor	Fatality Rate Mean	Fatality Rate COV	Injury Rate Mean	Injury Rate COV
Floor 4 (4)	1	0.5	1	0.5
Floor 3 (3)	1	0.5	1	0.5
Floor 2 (2)	1	0.5	1	0.5
Floor 1 (1)	0.9	0.5	1	0.5

Figure 4-16 PACT Collapse Fragility tab.

4.4.6.2 Collapse Modes

PACT collapse mode input includes the number of independent collapse modes that can occur and the probability of each. This is difficult to predict analytically. To determine these data, the user must use judgment based on building type, structural system, past experience, and analytical inferences. When using the simplified analysis approach, limited analytical information regarding potential collapse modes is available. For this example, only a single mode of collapse is considered. Additional information gained from numerous response history analyses can provide additional insight into potential collapse modes.

PACT input also includes the fraction of each floor subject to collapse-associated debris and the resulting fatality and injury rates. These must also be determined judgmentally. Figure 4-16 shows the input values for this example.

4.4.7 Residual Drift Fragility

The PACT default residual drift fragility function is modified for this assessment. The median residual drift ratio at which damage will be deemed irreparable is increased to 0.0125. The estimated median building residual drift ratio demand and dispersion are input into the PACT **Residual Drift** tab after the analysis is completed.

4.5 Select Analysis Method and Construct Building Analytical Model

Simplified analysis is used to generate median estimates of peak transient drift, peak floor accelerations and residual drifts. Associated dispersions are generated using simplified analysis. Peak total floor velocities are not generated since none of the vulnerable building components use this demand parameter. A linear building model is constructed using the modeling criteria of ASCE/SEI 41-13 (ASCE, 2014), linear static procedure.

4.6 Define Earthquake Hazards

The target intensity is given as earthquake ground shaking with an average return period of 475 years. In order to estimate median values of story drift ratios, peak floor accelerations, and residual drift ratios, the following ground motion parameters will be required: $S_a(T_1^X)$, $S_a(T_1^Y)$, and $S_a(T=0)$. These parameters are obtained by using the steps outlined in Section 3.3.2.1 and Section 3.5.2.1.

Step 1. In order to determine the building's fundamental translational periods in two orthogonal directions, modal analysis is performed. For this doubly symmetric building $T_1^X = T_1^Y = 1.13$ seconds.

Step 2. The first mode average period is $\bar{T} = 1.13$ seconds since T_1^X and T_1^Y are identical.

Step 3. Obtain a seismic hazard curve for $S_a(\bar{T})$.

The following tools provided by the USGS that can be used to obtain a seismic hazard curve at the site: (1) the *Unified Hazard Tool* (<https://earthquake.usgs.gov/hazards/interactive/>, last accessed March 15, 2018); and (2) the *Java Ground Motion Parameter Calculator*. This example uses the *Java Calculator* to construct the hazard curve. The basic information necessary to generate the seismic hazard curve using this approach includes the site latitude and longitude (accurate to three decimal places), the average period, \bar{T} , and the site class as defined in ASCE/SEI 7-10.

The example building is located in the Los Angeles area with: Latitude: 33.996°, Longitude: -118.162°, and Site Class D.

The *Java Ground Motion Calculator* provides spectral acceleration hazard curves for sites conforming to ASCE/SEI 7-10 Site Class B at the following building periods: 0, 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 seconds at the building location. For intermediate periods, the value of S_a can be determined by constructing the spectrum using the above periods and graphically determining the value of $S_a(T)$. For structures in the period range of 0.7 to 2.0 seconds, it is generally considered sufficiently accurate to obtain $S_a(T)$ from the formula:

$$S_a(T) = \frac{S_a(1.0)}{T}$$

Figure 4-17 illustrates the *Java Ground Motion Calculator* input and tabular output for spectral acceleration values at 1.0 second period and their mean annual frequency of exceedance at the building site, assuming Site Class B conditions.

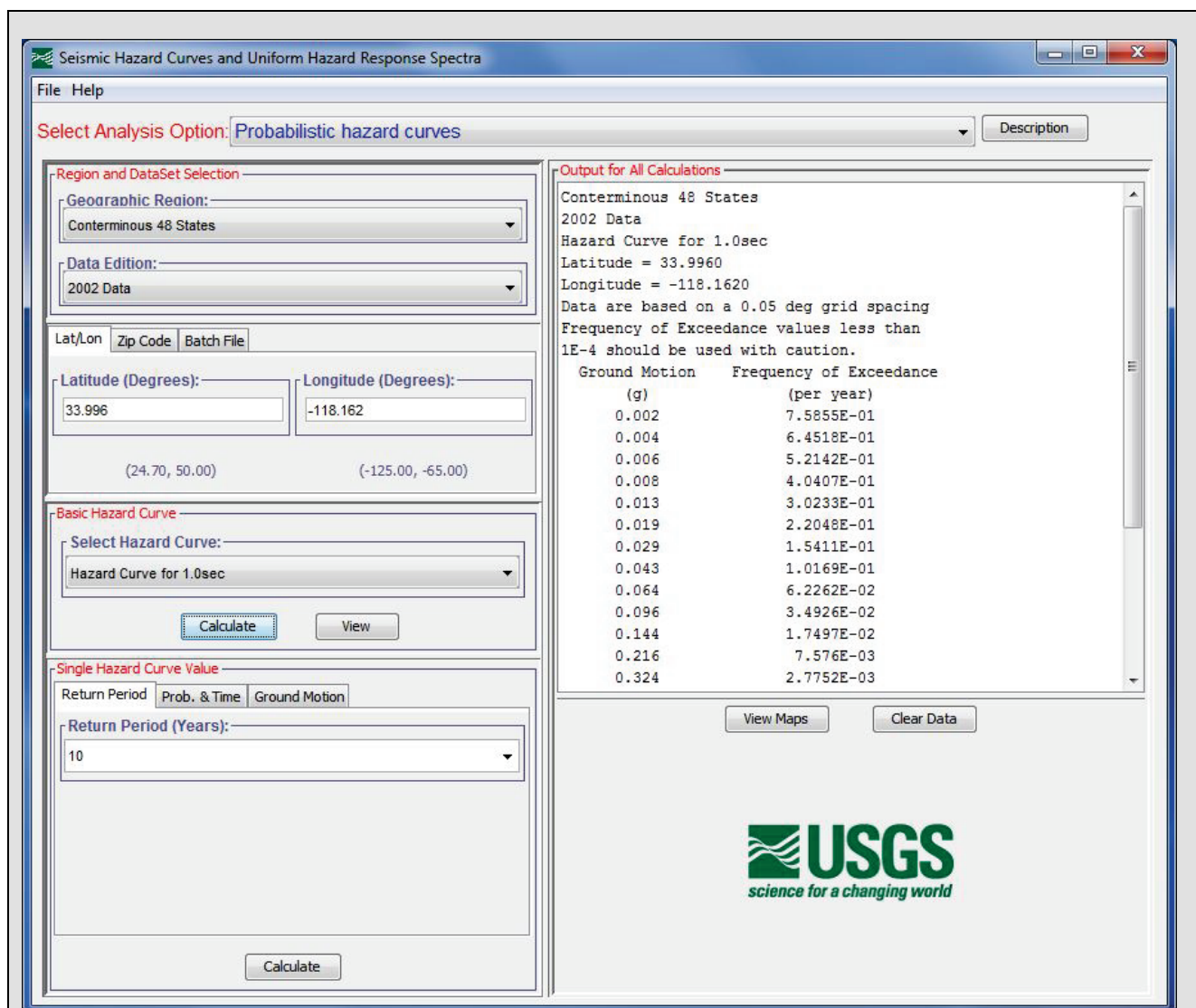


Figure 4-17 USGS hazard data for 1.0 second period at Site Class B.

Table 4.5 shows the spectral acceleration values (at 1.0s) and mean annual frequency of exceedance, λ , values obtained from the ground motion calculator, and values of $S_a(1.13s)$ derived using the above formula with $\bar{T} = 1.13s$. The table also provides values of F_v obtained from ASCE/SEI 7-10 at each λ and the corresponding $S_a(1.13s)$ values at Site Class D, using F_v . Figure 4-18 is a plot of these data evaluated at the building average period at Site Class D and presented in log-linear form.

Table 4-5 USGS Hazard Data, Adjusted for Building Period and Site Class

$S_a(T=1.00s)$ Site Class B	λ	$S_a(T=1.13s)$ Site Class B	F_v	$S_a(T = 1.13s)$ Site Class D
0.002	0.75855	0.0018	2.4	0.00432
0.004	0.64518	0.0035	2.4	0.0084
0.006	0.52414	0.0052	2.4	0.01272
0.008	0.40407	0.0071	2.4	0.01704
0.013	0.30233	0.012	2.4	0.0288
0.019	0.22048	0.017	2.4	0.0408
0.029	0.15411	0.026	2.4	0.0624
0.043	0.10169	0.038	2.4	0.0912
0.064	0.06226	0.057	2.4	0.1368
0.096	0.034926	0.084	2.4	0.204
0.144	0.017497	0.127	2.2	0.2921
0.216	0.007576	0.191	2.0	0.382
0.324	0.002775	0.287	1.8	0.5166
0.487	0.000849	0.431	1.5	0.6896
0.730	0.00022	0.646	1.5	0.969
1.090	0.000048	0.965	1.5	1.4475
1.640	0.000008	1.451	1.5	2.1765
2.460	0.000001	2.177	1.5	3.2654

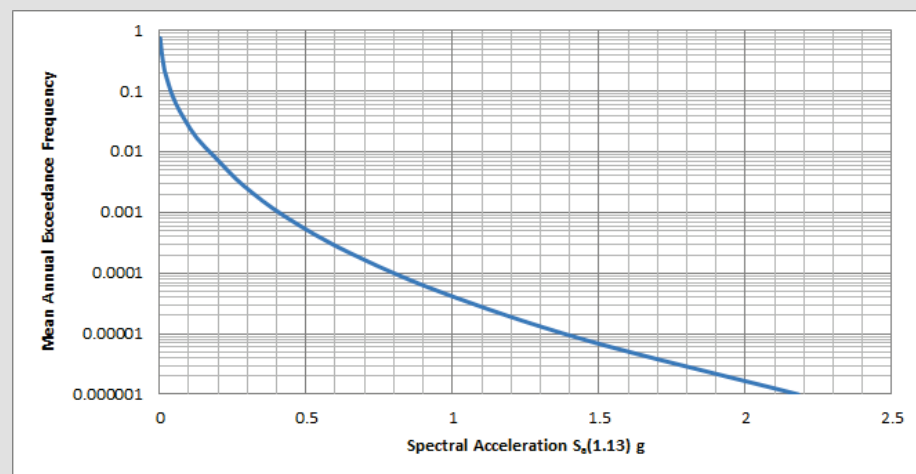


Figure 4-18 Seismic hazard curve for $S_a(T = 1.13s)$, Site Class D.

The mean annual frequency of exceedance for ground shaking intensity with a mean return period of 475 years is $1/475 = 0.002105$. From Table 4-5, the S_a ($T = 1.13$ s) value at Site Class B corresponding to this λ , is 0.381g. Adjusting this value for Site Class B using the site coefficient, F_v (value of 1.7 for S1 between 0.3 and 0.4 in from ASCE/SEI 7-10 Table 11.4-2), yields $S_a(1.13s) = 1.7 \times 0.381g = 0.648g$.

The *Java Ground Motion Calculator* can also be used to generate the peak ground acceleration at the site for a return period of 475 years, as shown in Figure 4-19. The value of the peak ground acceleration is identified as 0.419g.

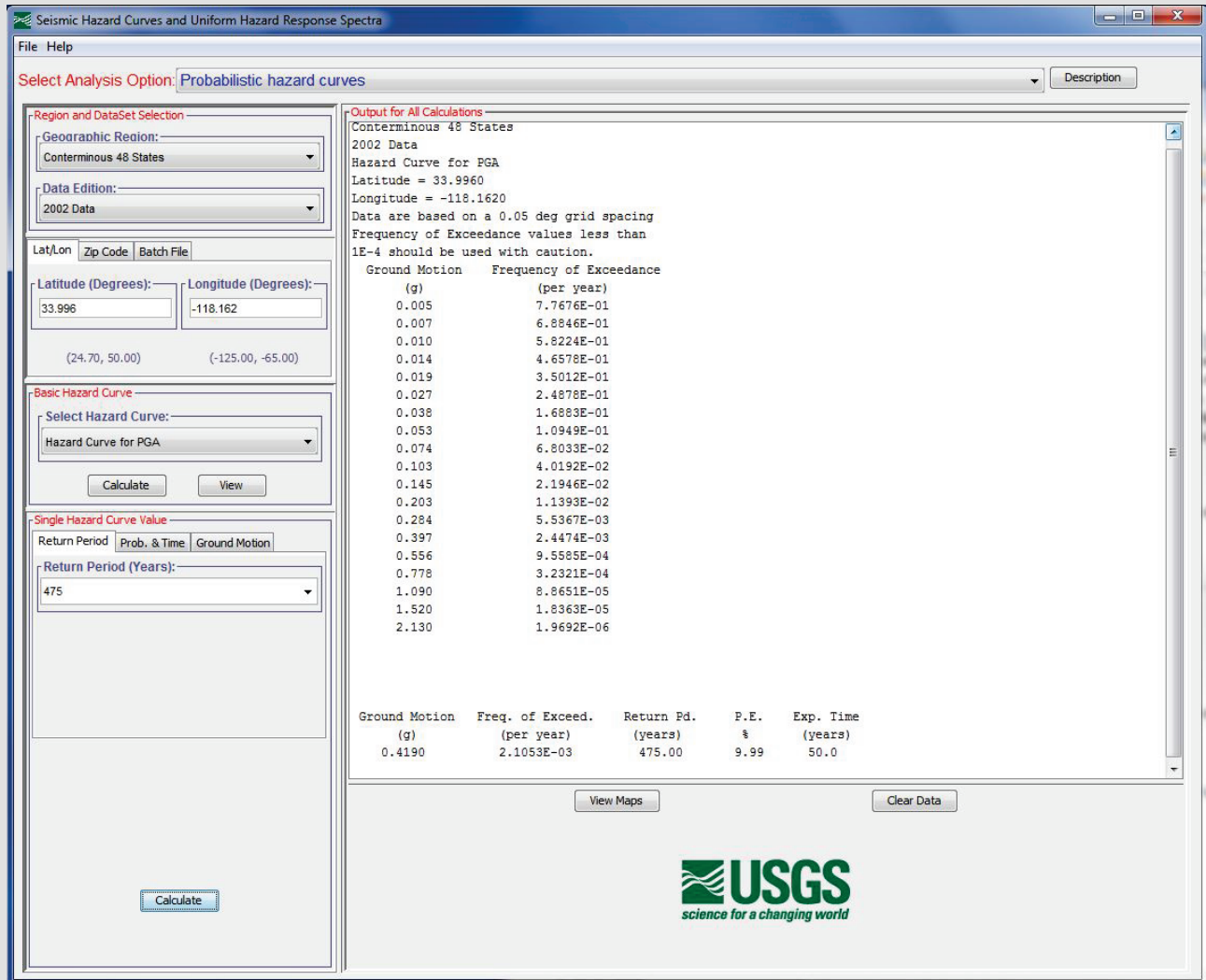


Figure 4-19 USGS hazard data for peak ground acceleration.

Using ASCE/SEI 7-10 Table 11.4-1 which provides a conversion factor, F_a , for ranges of S_s (the S_a value at 0.2 seconds), an appropriate value is selected to adjust the peak ground acceleration value to reflect site class. Peak ground acceleration can be related to S_s for this purpose by factoring peak ground acceleration by 2.5, yielding a value of 1.1g.

Returning to ASCE/SEI 7-10 Table 11.4-1 with $S_s = 1.1$, a value of $F_a = 1.1$ is selected.

The resulting site adjusted peak ground acceleration is: $1.1 \times 0.419g = 0.461g$.

4.7 Analyze Building Response

Following the steps outlined in Section 3.3.2.2, median estimates and dispersions of peak transient drift ratio, peak floor acceleration, and residual drift ratio are generated using the simplified analysis approach.

4.7.1 Estimate Median Story Drift Ratio and Dispersion

Step 1. Determine pseudo lateral force.

$$V = C_1 C_2 S_a(T_1) W_1$$

$T_1 = 1.13$ seconds; $S_a(1.13s) = 0.648g$; $W = 8365.6$ kips

for $T_1 \geq 1.0$ seconds, $C_1 = C_2 = 1.0$

Step 2. Distribute forces vertically, as shown in Table 4-6.

Table 4-6 Lumped Weight Distribution

Story	W	h (in.)	$\frac{wh}{\sum wh}$
4	2091.4	648	0.391
3	2091.4	492	0.297
2	2091.4	336	0.203
1	2091.4	180	0.109

Step 3: Calculate displacements and drift ratios.

Using a linear modeling representation of the building consistent with ASCE/SEI 41-13, the following displacements are calculated, see Figure 4-20:

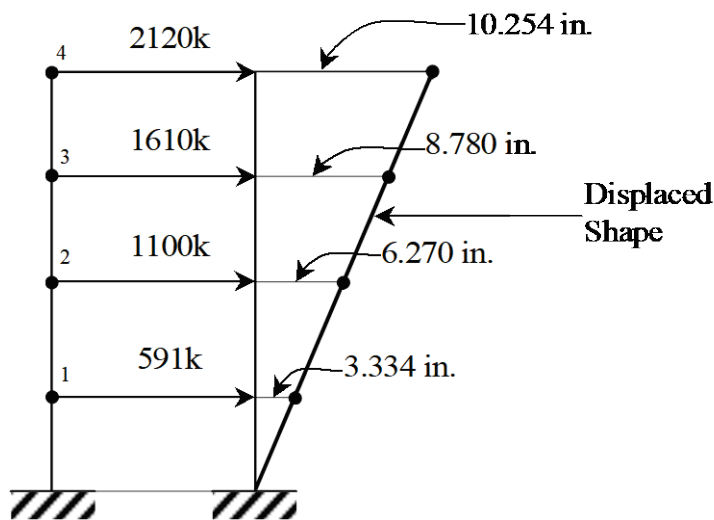


Figure 4-20 Results from linear analysis.

The corresponding drift ratios are:

$$\Delta_2 = \frac{3.334}{180} = 0.01852$$

$$\Delta_3 = \frac{6.270 - 3.334}{156} = 0.01882$$

$$\Delta_4 = \frac{8.780 - 6.270}{156} = 0.0161$$

$$\Delta_r = \frac{10.254 - 8.780}{156} = 0.00945$$

Step 3. Obtain estimates of median story drift ratio, Δ_i^* , at each story by correcting for inelastic behavior and higher modes using Volume 1, Equation 5-10:

$$\Delta_i^* = H_{\Delta i}(S, T_l, h_i, H) \times \Delta_i \quad i = 1 \text{ to } N$$

where $H_{\Delta i}(S, T_l, h_i, H)$ is the drift modification factor for story i computed using Volume 1, Equation 5-11:

$$\ln(H_{\Delta i}) = a_0 + a_1 T_l + a_2 S + a_3 \frac{h_{i+1}}{H} + a_4 \left(\frac{h_{i+1}}{H} \right)^2 + a_5 \left(\frac{h_{i+1}}{H} \right)^3, \quad S \geq 1, i = 1 \text{ to } N$$

with $T_l = 1.13\text{s}$, $H = 648$ inches

Values for coefficients a_0 through a_5 for buildings 9 stories or less in height are provided in Volume 1, Table 5-4. For a 4-story moment frame structure, the coefficients are as follows:

$$a_0 = 0.75, a_1 = -0.044, a_2 = -0.010, a_3 = -2.58, a_4 = 2.30, a_5 = 0.0$$

$$S = \frac{S_a(T_l) W}{V_{y1}}$$

$$S_a(T_l) = 0.648g, W = 8365.6 \text{ kips}$$

The value of V_{y1} is taken from the pushover analysis used to estimate the collapse fragility (see SPO2IDA input, Figure 4-14, Elastic Segment endpoint) as 1066 kips.

$$S = \frac{0.648(8365.6)}{1066} = 5.09$$

Table 4-7 summarizes the calculation for converting calculated peak story drift ratio into a median estimate of peak story drift ratio.

Table 4-7 Median Story Drift Ratio Estimates

Story	Δ_i	$\frac{h_{i+1}}{H}$	$\ln H_{\Delta i}$	$H_{\Delta i}$	Δ_i^*
1	0.01852	0.28	0.1073	1.113	0.0206
2	0.01882	0.52	-0.0707	0.9317	0.0175
3	0.01610	0.76	0.01708	1.0172	0.0164
4	0.00945	1.00	0.3694	1.4469	0.0137

Step 4. Assign dispersions.

From Table 3-4 with $T_l = 1.13\text{s}$ and $S = 5.09$ β_{SD} is obtained by interpolation to be 0.59.

4.7.2 Estimate Median Peak Floor Acceleration and Dispersion

Step 1. Generate median peak floor accelerations.

$$a_i^* = H_{ai}(S, T_l, h_i, H) \times PGA \quad i = 2 \text{ to } N + 1$$

$$S = 5.09, T_l = 1.13\text{s}, H = 648 \text{ inches}, PGA = 0.461g$$

$$\ln(H_{ai}) = a_0 + a_1 T_l + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H} \right)^2 + a_5 \left(\frac{h_i}{H} \right)^3, S \geq 1, i = 2 \text{ to } N + 1$$

where the values for coefficients a_0 through a_5 for a moment frame structure are given in Volume 1, Table 5-4 are as follows:

$$a_0 = 0.66, a_1 = -0.25, a_2 = -0.080, a_3 = -0.039, a_4 = 0.0, a_5 = 0.0$$

Table 4-8 summarizes the results of application of the above expressions to generate median estimates of peak floor acceleration.

Table 4-8 Median Floor Acceleration Estimates

Floor	PGA	$\frac{h_i}{H}$	$\ln H_{Ai}$	H_{Ai}	a_i^*
1	0.461	-	-	-	0.461
2	0.461	0.28	-0.04062	0.9602	0.443
3	0.461	0.52	-0.05000	0.9512	0.439
4	0.461	0.76	-0.05934	0.9424	0.434
Roof	0.461	1.00	-0.06870	0.9336	0.430

Step 2. Assign dispersions.

From Table 3-5 with $T_I = 1.13$ s and $S = 5.09$ β_{FA} is obtained by interpolation to be 0.48.

4.7.3 Estimate Median Residual Story Drift Ratio and Dispersion

Step 1. Generate median residual drift ratio.

Residual drift ratio is determined by the difference between peak transient drift ratio and median story drift ratio at yield. The peak transient drift ratios were estimated in Section 4.7.1. The yield drift ratio is obtained from the pushover analysis used to generate the story shear at yield. From Figure 4-15, the roof displacement at yield is 0.189 feet or 2.268 inches. Thus, the yield drift ratio is

$$\Delta_y = \frac{2.268}{648} = 0.00350$$

The maximum transient drift ratio for the building occurs at the first story (0.0206). The maximum residual drift ratio is therefore:

$$\Delta_r^* (\max) = 0.0206 - 3(0.0035) = 0.0101$$

Note that in this example, Δ_r^* is substantially greater than $4 \Delta_y$. This significantly exceeds the recommended limitation on the degree of inelastic behavior for which the linear approach is appropriate. At higher levels of nonlinearity, the effects of component degradation and P- Δ may result in an underestimation of median demand.

The median estimate of residual drift obtained from the simplified analysis method is assigned a dispersion of 0.8.

4.8 Input Response Data and Calculate Performance

The median demand estimates for peak transient drift ratio, peak floor acceleration, and residual drift ratio are input to PACT for direction 1 and direction 2 in the **Structural Analysis Results** tab. Figure 4-21 illustrates the input of peak transient drift ratio values. Residual drift ratio is input using the **Residual Drift** tab. Figure 4-22 illustrates input of the peak residual drift ratio and its associated dispersion on the lowest row of the tab.

The figure consists of two screenshots of the PACT Building Modeler software interface, specifically the 'Structural Analysis Results' tab. Both screenshots show the 'Intensity 1' direction selected, with a table of median story drift ratios for different floor levels. The top screenshot shows the 'Intensity 1' direction, and the bottom screenshot shows the 'Intensity 2' direction. Both screenshots show a 'Dispersion in Response for this Demand Type' input field set to 0.59.

Intensity 1

Floor/Story	Median
Level 4-Roof (rad)	0.0137
Level 3-4 (rad)	0.0164
Level 2-3 (rad)	0.0175
Level 1-2 (rad)	0.0206

Intensity 2

Floor/Story	Median
Level 4-Roof (rad)	0.0137
Level 3-4 (rad)	0.0164
Level 2-3 (rad)	0.0175
Level 1-2 (rad)	0.0206

Figure 4-21 PACT peak transient drift ratio input on Structural Analysis Results tab.

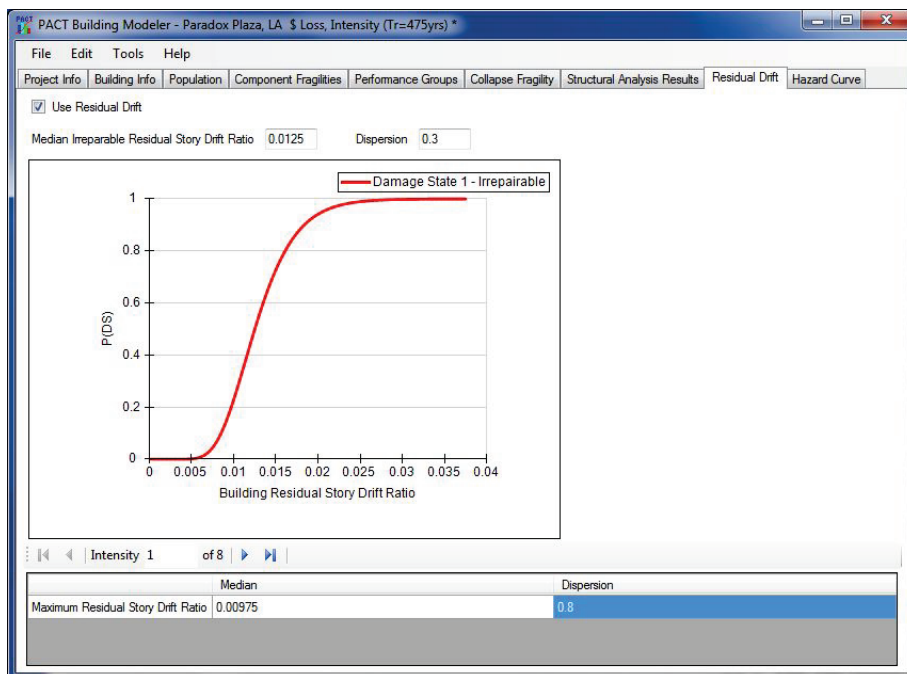


Figure 4-22 PACT Residual Drift tab.

The assessment can be executed by saving and exiting the model. After returning to the **PACT Control Panel**, pressing the **Evaluate Performance** button and identifying the assessment model will run the tool.

4.9 Review Results

Figure 4-23 provides illustrative results from PACT analysis. At the bottom of Figure 4-23, the estimated median repair cost is shown as \$5,126,667, which corresponds to 23.7% of the example building's total replacement cost. The top half of the figure can be used to identify the contribution of different fragility groups to the repair cost total. If one type of component is identified as having a large contribution, e.g., partitions fixed at top and bottom, replacement with an alternate configuration of the component, e.g., slip track partitions, could reduce the report cost total. After such consideration the performance assessment model can be revised and rerun with PACT.

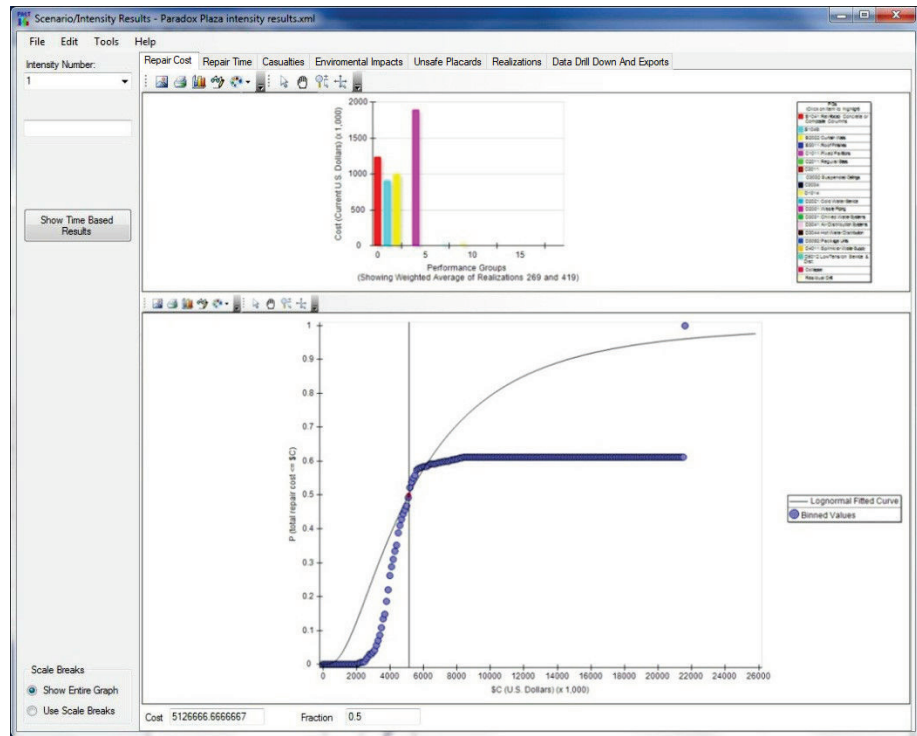


Figure 4-23 PACT Repair Cost tab.

Performance results from PACT can be examined in numerous ways. Viewing results by realization reveals that residual drift plays a more significant role than collapse (see Figure 4-24). For approximately 186 of the 500 realizations, residual drift resulted in the damage being judged irreparable.

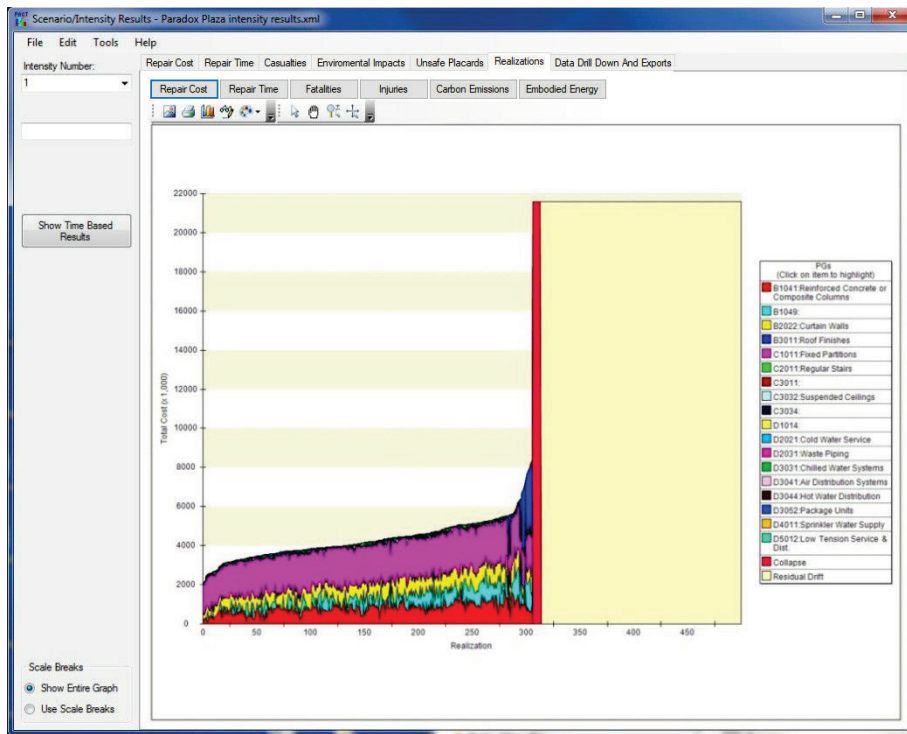


Figure 4-24 PACT Repair Cost tab with realizations.

Chapter 5

Example Application: Time-Based Performance Assessment Using Nonlinear Response History Analysis

5.1 Introduction

This chapter provides an example application of the time-based performance assessment methodology using nonlinear response history analysis in the *Performance Assessment Calculation Tool* (PACT) with provided fragility and consequence function data.

The work necessary to obtain a probable maximum loss value that reflects the repair cost, expressed as percentage of building replacement cost, having a 10% probability of exceedance over a 30-year loan period for an office building is presented here as follows:

- Obtain site and building description (Section 5.2)
- Select assessment type and performance measure (Section 5.3)
- Assemble building performance model (Section 5.4)
- Select analysis method and construct analytical building model (Section 5.5)
- Define earthquake hazards (Section 5.6)
- Analyze building response (Section 5.7)
- Input response data and calculate performance (Section 5.8)
- Review results for selected performance measures (Section 5.9)

5.2 Obtain Site and Building Description

The example uses the same building and performance assessment model as Chapter 4 with some modifications. Section 4.2, provides a detailed building description. In summary, the building is a 4-story reinforced concrete structure with commercial office occupancy located in Los Angeles, California.

5.3 Select Assessment Type and Performance Measures

Time-based assessment will be performed with building performance expressed in terms of average annual repair cost in dollars. The resulting cost distribution is used to determine the loss associated with a 10% probability of exceedance over a 30-year period of time and converted from dollars to percentage of replacement cost.

5.4 Assemble Performance Assessment Model

Section 4.4 describes performance assessment model assembly in detail. However, the following additions and changes to the assessment model are made for this assessment:

- Performance groups are identified with uncorrelated components to obtain an improved estimate of the performance variability.
- The collapse modes identified and input to the assessment model are expanded to include partial collapse. As a result of information obtained from response history analyses used to generate analysis input, a partial collapse mode is added to the previously defined total collapse mode. The partial collapse mode consists of sidesway failure of the top floor. This mode does not lead to collapse of the lower floors. Collapse mode 1 from the previously developed assessment model is revised to reflect an occurrence probability (given that collapse occurs) of 0.5. Collapse mode 2 is similarly assigned a probability of 0.5. Table 5-1 summarizes the salient collapse characteristics.
- Structural analysis results are input for 8 ground shaking intensities and 7 ground motions for each intensity level. Each demand vector, associated with one ground motion includes input for peak story drift and floor acceleration at each level in each direction and maximum residual story drift.

Table 5-1 Collapse Mode Consequences

Mode	Collapse Debris Floor Fraction				Fatality Rate with COV = 0.5				Injury Rate with COV = 0.5			
	4	3	2	1	4	3	2	1	4	3	2	1
1	1	1	1	1	1	1	1	1	0	0	0	0
2	1	0	0	0	1	0	0	0	0	0	0	0

5.5 Select Analysis Method and Construct Building Analytical Model

The structure is analyzed using nonlinear response history analysis. A three dimensional analytical model is assembled as described in Section 3.2.2 and Volume 1, Chapter 5.

5.6 Define Earthquake Hazards

Time-based assessment requires execution of the procedure presented in Section 3.5.1. The nine steps described in that section are illustrated below for the example building.

Step 1 through Step 3 were illustrated in Section 4.6 and the results are repeated here.

Step 1. The building's fundamental translational periods in two orthogonal directions, are $T_I^X = T_I^Y = 1.13$ seconds.

Step 2. The first mode average period is $\bar{T} = 1.13$ seconds since T_I^X and T_I^Y are identical.

Step 3. Obtain a seismic hazard curve for $S_a(\bar{T})$.

Although site-specific seismic hazard analysis can be used, for this example, the USGS *Java Ground Motion Calculator* is used, as previously illustrated in Figure 4-17.

For intermediate periods, the value of S_a can be determined by constructing the spectrum using the above periods and graphically determining the value of $S_a(T)$. For structures in the period range of 0.7 to 2.0 seconds, it is generally considered sufficiently accurate to obtain $S_a(T)$ from the formula:

$$S_a(T) = \frac{S_a(1.0)}{T}$$

Table 5-2 shows the spectral acceleration values (at 1.0s) and mean annual frequency of exceedance, λ , values obtained from the ground motion calculator, and values of $S_a(1.13s)$ derived using the above formula with $\bar{T} = 1.13s$. The table also provides values of F_v obtained from ASCE/SEI 7-10 at each λ and the corresponding $S_a(1.13s)$ values at Site Class D, using F_v . Figure 5-1 is a plot of these data evaluated at the building average period at Site Class D and presented in log-linear form.

Table 5-2 Hazard Data, Adjusted for Building Period and Site Class

$S_a(T=1.00s)$ Site Class B	λ	$S_a(T=1.13s)$ Site Class B	F_v	$S_a(T = 1.13s)$ Site Class D
0.002	0.75855	0.0018	2.4	0.00432
0.004	0.64518	0.0035	2.4	0.0084
0.006	0.52414	0.0052	2.4	0.01272
0.008	0.40407	0.0071	2.4	0.01704
0.013	0.30233	0.012	2.4	0.0288
0.019	0.22048	0.017	2.4	0.0408
0.029	0.15411	0.026	2.4	0.0624
0.043	0.10169	0.038	2.4	0.0912
0.064	0.06226	0.057	2.4	0.1368
0.096	0.034926	0.084	2.4	0.204
0.144	0.017497	0.127	2.2	0.2921
0.216	0.007576	0.191	2.0	0.382
0.324	0.002775	0.287	1.8	0.5166
0.487	0.000849	0.431	1.5	0.6896
0.730	0.00022	0.646	1.5	0.969
1.090	0.000048	0.965	1.5	1.4475
1.640	0.000008	1.451	1.5	2.1765
2.460	0.000001	2.177	1.5	3.2654

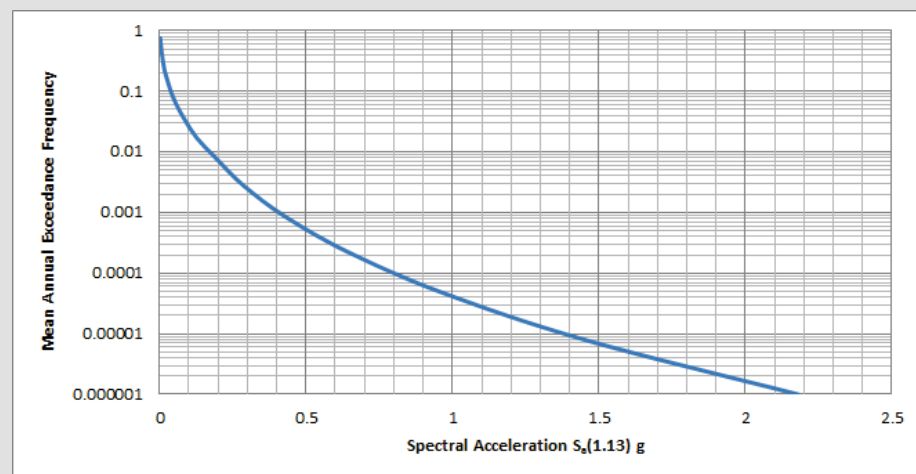


Figure 5-1 Seismic hazard curve for $S_a(T = 1.13s)$, Site Class D.

Step 4. Define $S_a^{min}(T)$ and $S_a^{max}(T)$ that span between building response that produces negligible damage to response that produces significant probability of collapse. For $\bar{T}=1.13\text{s}$, $S_a^{min}(\bar{T})$ can be taken as:

$$S_a^{min}(\bar{T}) = \frac{0.05}{\bar{T}} = \frac{0.05}{1.13} = 0.044\text{g}$$

$S_a^{max}(\bar{T})$ need not be taken larger than the median collapse capacity or alternatively as $2 \times S_a(\bar{T})$ with a λ of 0.0004.

From Section 4.4.5.1 the structure's median collapse capacity $\hat{S}_a(\bar{T}) = 2.23\text{g}$.

From Figure 5-1 the $S_a(\bar{T})$ value is interpolated as 0.935g. Twice this value is 1.87g, which is taken as $S_a^{max}(\bar{T})$.

Step 5. Divide the seismic hazard curve into 8 segments that span the range of $\hat{S}_a(\bar{T})$ from $S_a^{min}(\bar{T})$ to $S_a^{max}(\bar{T})$.

Figure 5-2 illustrates the striping of the seismic hazard curve of Figure 5-2 producing 8 equal S_a -width segments spanning the range of $\hat{S}_a(\bar{T})$ from 0.044g to 1.87g ($S_a^{min}(\bar{T})$ to $S_a^{max}(\bar{T})$). Each segment has a width

$$\frac{1.87 - 0.044}{8} = 0.228\text{g}$$

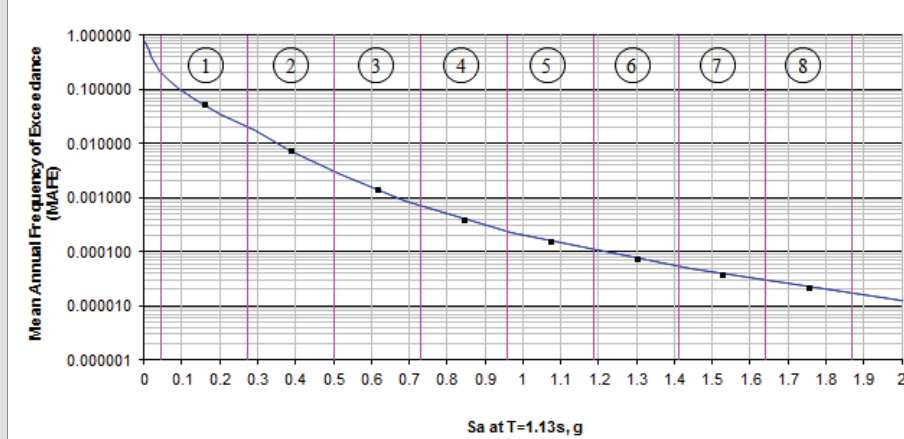


Figure 5-2 Segmented seismic hazard curve to be used for time-based assessment.

Step 6. The central value of $\hat{S}_a(\bar{T})$ at the midpoint of each segment is determined together with its mean annual frequency of exceedance. Table 5-3 summarizes these data.

Table 5-3 Intensity Segment Values

Spectral Segment	\bar{S}_a	λ
1	0.158	0.05364
2	0.387	0.00740
3	0.615	0.00170
4	0.843	0.00050
5	1.071	0.00018
6	1.299	0.000101
7	1.528	0.0000435
8	1.756	0.0000311

For $S_a(\bar{T})_{\min} = 0.044$, the corresponding λ value is 0.2106. For $S_a(\bar{T})_{\max} = 1.87g$, the corresponding λ value is 0.00002495.

Step 7. For each spectral segment, a response spectrum is constructed that is used for the ground motion scaling of Step 8. Uniform Hazard Spectra (UHS), Conditional Mean Spectra (CMS) or Conditional Spectra (CS) can be used for this purpose. For events with a relatively large frequency both the UHS and CMS should have similar shapes and are appropriate for use. For small frequency (infrequent) events, use of the CMS or CS spectra should improve estimates of drift and accelerations over those generated using UHS spectra. For this example, UHS spectra will be used for segments 1 and 2, which have mean annual return periods of 11.2 and 152.1 years respectively. For segments 3 through 8, CMS spectra will be used for selecting and scaling ground motions.

Construction of a UHS for segments 1 and 2 can be accomplished using the *Java Ground Motion Parameter Calculator* with the Probabilistic Uniform Hazard Response Spectra analysis option, as illustrated in Figure 5-3. The spectral shape can be considered constant for λ segments up to 0.002105. For less frequent hazard intensities, see ASCE/SEI 41-06, Section 1.6 for UHS spectral adjustments.

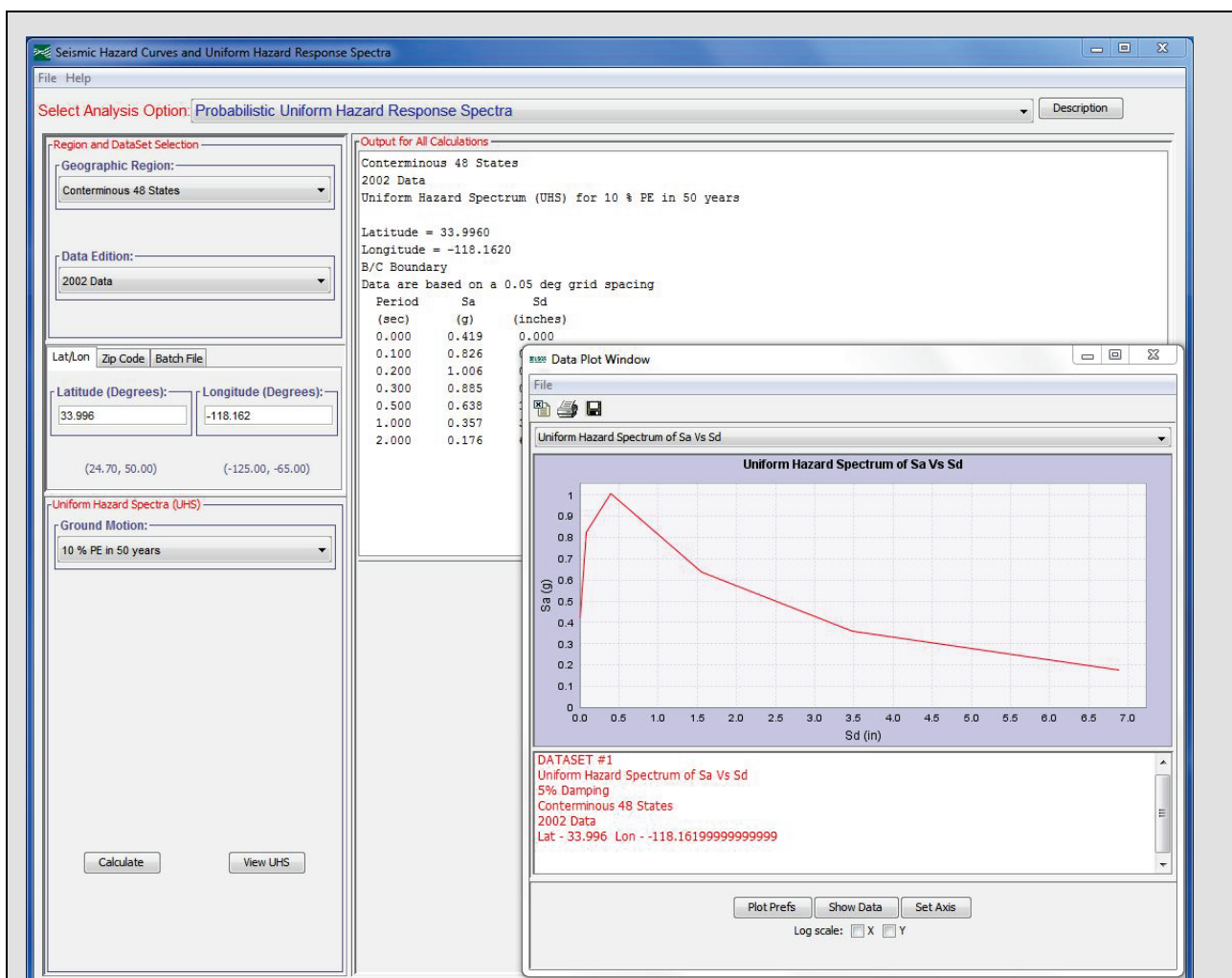


Figure 5-3 Uniform Hazard Spectrum.

Table 5-4 summarizes deaggregation results for segments 3 through 8. Figure 5-4 illustrates a sample deaggregation for segment 3. This tool can also be used to directly generate conditional mean spectra from the deaggregation information.

Table 5-4 Deaggregation Summary

Segment	S_a	λ	M	R	ε
3	0.615	0.0016	6.9	18	0.9
4	0.843	0.00064	6.9	18	1.5
5	1.071	0.00032	6.9	13	1.6
6	1.299	0.00018	6.8	10	1.7
7	1.528	0.00010	6.8	8	1.7
8	1.756	0.00004	6.8	7	1.8

These data can be used to construct a conditional mean spectrum for each intensity segment. Figure 5-6 illustrates the conditional mean spectrum generated for segment 3 by the USGS calculator.

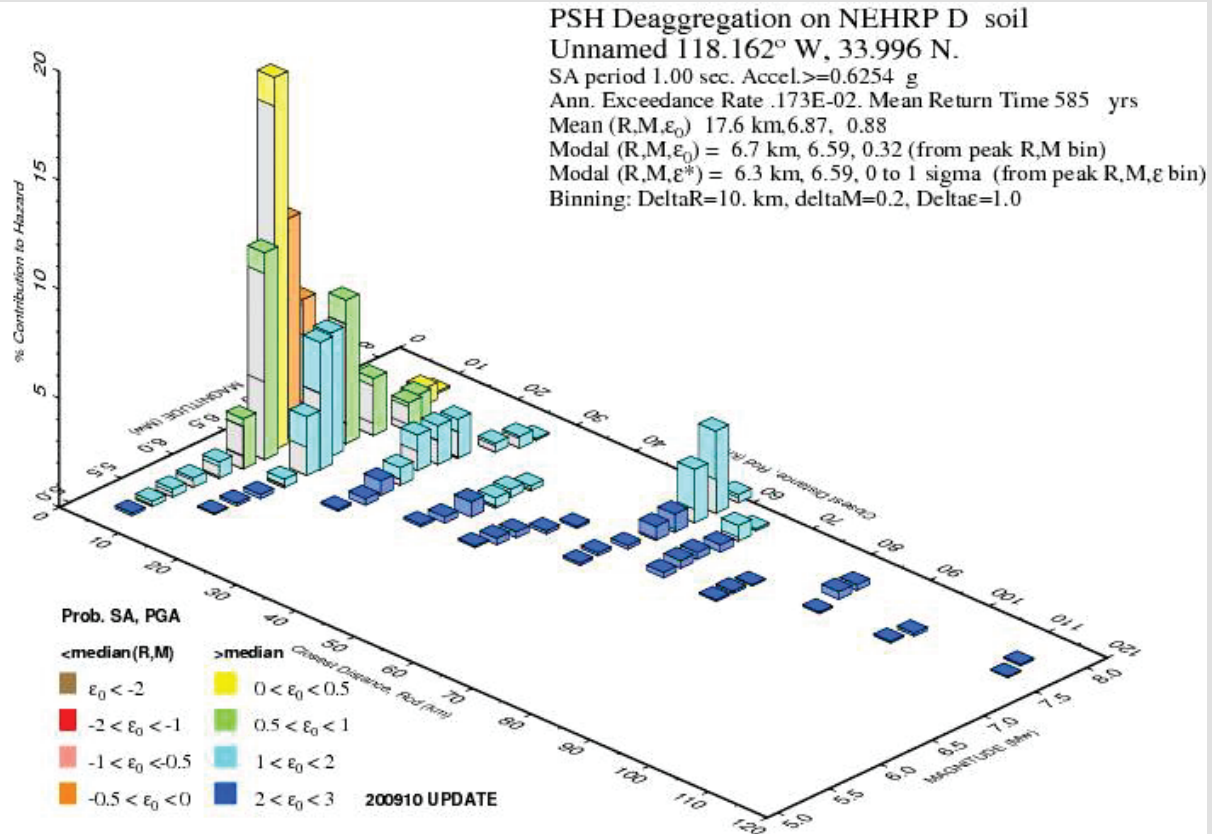


Figure 5-4 Deaggregation of segment 3.

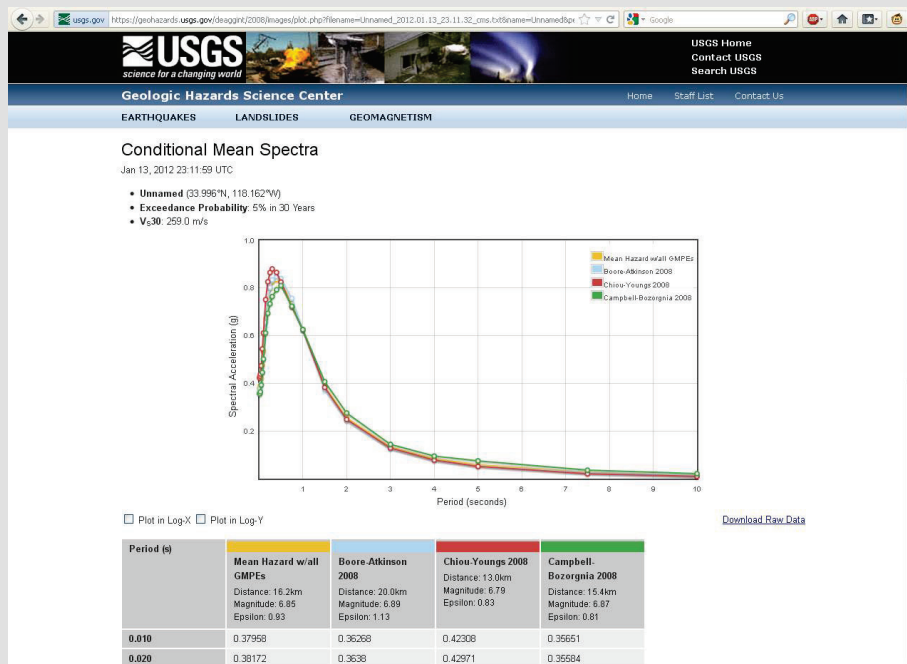


Figure 5-5 Conditional mean spectrum for segment 3.

Step 8. Select and scale the geomean of ground motion record pairs to the amplitude of the target spectrum at the $S_a(\bar{T})$ as illustrated in Section 3.3.1.1 for intensity-based assessment. Ground motions for selection and scaling can be found at <https://ngawest2.berkeley.edu/>, www.cosmos-eq.org (last accessed March 15, 2018) and other websites. The PEER website also provides software tools for spectral shape matching and scaling of ground motion records, and a tool that can be used to select and scale record pairs to any user defined spectrum.

An alternate site with tools to assist in selection and scaling include can be found at <http://www.stanford.edu/~bakerjw/>. This site provides a tool for selecting and scaling record pairs from the PEER database to match a conditional mean target spectrum. A minimum of 7 well matched pairs of records is recommended. For further discussion of the number of records needed to produce statistically valid analysis results, see Volume 1.

Step 9. Repeat Step 8 for each spectral segment.

5.7 Analyze Building Response

Seven ground motions were selected and scaled for each of the eight intensities. Table 5-5 summarizes structural response data obtained from response history analysis at each of the eight intensities. Note that the selected records for this example came from NGA West database that has now been superseded by the NGA-West2 database.

As noted in Section 3.3.1.2 and Volume 1, Chapter 5, the analytically generated median drift and acceleration estimates are assigned dispersions to reflect response variability. The assigned dispersion, β_m , is composed of two components, β_c and β_q . Values for each are provided in Volume 1, Table 5-1 and Volume 1, Table 5-2 and are reproduced in Volume 2 as Table 3-1 and Table 3-2.

Table 5-5 Summary of Structural Analysis Results

Intensity 1 $S_a(\bar{T})=0.158$ g		Intensity 2 $S_a(\bar{T})=0.387$ g	
Demand Parameter	Median	Parameter	Median
Δ_4	0.002	Δ_4	0.003
Δ_3	0.004	Δ_3	0.008
Δ_2	0.005	Δ_2	0.0134
Δ_1	0.005	Δ_1	0.010
a_5	0.24	a_5	0.34
a_4	0.18	a_4	0.30
a_3	0.19	a_3	0.30
a_2	0.16	a_2	0.30
a_1	0.19	a_1	0.22
Intensity 3 $S_a(\bar{T})=0.615$ g		Intensity 4 $S_a(\bar{T})=0.843$ g	
Demand Parameter	Median	Parameter	Median
Δ_4	0.006	Δ_4	0.008
Δ_3	0.013	Δ_3	0.019
Δ_2	0.017	Δ_2	0.024
Δ_1	0.015	Δ_1	0.022
a_5	0.43	a_5	0.48
a_4	0.36	a_4	0.41
a_3	0.38	a_3	0.48
a_2	0.43	a_2	0.53
a_1	0.36	a_1	0.48
Intensity 5 $S_a(\bar{T})=1.071$ g		Intensity 6 $S_a(\bar{T})=1.299$ g	
Demand Parameter	Median	Parameter	Median
Δ_4	0.012	Δ_4	0.011
Δ_3	0.024	Δ_3	0.025
Δ_2	0.030	Δ_2	0.039
Δ_1	0.029	Δ_1	0.037
a_5	0.49	a_5	0.55
a_4	0.44	a_4	0.45
a_3	0.48	a_3	0.52
a_2	0.59	a_2	0.69
a_1	0.52	a_1	0.68

Δ_i : Maximum drift ratio at story i

a_i : Peak floor acceleration at floor i

Table 5-5 Summary of Structural Analysis Results (continued)

Intensity 7 $S_a(\bar{T}) = 1.528 \text{ g}$		Intensity 8 $S_a(\bar{T}) = 1.756 \text{ g}$	
Demand Parameter	Median	Demand Parameter	Median
Δ_4	0.017	Δ_4	0.019
Δ_3	0.029	Δ_3	0.041
Δ_2	0.042	Δ_2	0.069
Δ_1	0.040	Δ_1	0.067
a_5	0.61	a_5	0.700
a_4	0.58	a_4	0.800
a_3	0.58	a_3	0.610
a_2	0.87	a_2	1.057
a_1	0.89	a_1	1.000

Δ_i : Maximum drift ratio at story i

a_i : Peak floor acceleration at floor i

For this example:

$$\beta_c = 0.25 \text{ and } \beta_q = 0.40$$

$$\beta_m = \sqrt{(0.25)^2 + (0.40)^2} = 0.47$$

Residual drift is determined from the peak transient drift associated with each demand vector for a given intensity. The drift with the largest ratio of transient drift to yield drift for direction 1 and direction 2 for each demand vector (EQ1, EQ2, EQ3, etc.) is selected. The residual drift ratio is calculated using the values of transient story drift, Δ_{max} , and the yield story drift, Δ_y , as follows:

$$\Delta_r = 0 \quad \text{for } \Delta_{max} < \Delta_y$$

$$\Delta_r = 0.3(\Delta_{max} - \Delta_y) \quad \text{for } \Delta_y < \Delta_{max} < 4\Delta_y$$

$$\Delta_r = \Delta_{max} - 3(\Delta_y) \quad \text{for } \Delta_{max} \geq 4\Delta_y$$

The value of yield drift, Δ_y , was determined in Chapter 4 for the example building as $\Delta_y = 0.00350$.

Table 5-6 displays maximum and residual drift values from each analysis for intensity 1. For this intensity, peak drifts do not exceed four times the yield drift ($4 \times 0.0035 = 0.014$) therefore $\Delta_r = 0.3(\Delta_{max} - \Delta_y)$.

Table 5-6 Residual Drift, Intensity 1

Intensity 1: $S_a = 0.158g$							
	1	2	3	4	5	6	7
Δ_{max}	0.007	0.005	0.005	0.005	0.006	0.005	0.005
Δ_r	0.00105	0.00045	0.00045	0.00045	0.00075	0.00045	0.00045

Table 5-7 illustrates the maximum story drifts and residual drifts calculated for intensity 3. For this intensity, peak drifts exceed $4\Delta_y$ and therefore $\Delta_r = \Delta_{max} - 3(\Delta_y)$

Table 5-7 Residual Drift, Intensity 3

Intensity 3: $S_a = 0.615g$							
	1	2	3	4	5	6	7
Δ_{max}	0.023	0.022	0.022	0.018	0.030	0.023	0.020
Δ_r	0.0125	0.015	0.015	0.0075	0.0195	0.0125	0.0095

Residual drift estimates are assigned a dispersion of 0.8.

The analysis results are used by PACT to indicate a statistical distribution of response states given that the building does not collapse. Initially, 7 scaled ground motion record pairs were selected, scaled, and analyzed for each intensity level. Collapse did not occur during any of the analyses for intensities 1, 2, 3, 4, or 5. However, for intensities 6, 7, and 8, collapse, indicated by lack of analysis convergence, did occur for some of the analyses.

For intensity 6, collapse occurred for one of the analyses and the results of that analysis were discarded. As discussed in Section 3.3.1.2 and Volume 1, Section 5.2.2, when the remaining number of ground motion pairs for which collapse did not occur is less than 7 and the probability of collapse for the spectral segment does not exceed 0.5 ($S_a(\bar{T}) \leq \hat{S}_a(\bar{T})$), the remaining sets of analyses ($n-q$) may not produce a valid estimate of demands when collapse does not occur. Since $S_a(\bar{T}) = 1.299g$ is less than the median collapse estimate for the structure ($\hat{S}_a(\bar{T}) = 2.23g$), an additional analysis was performed with a new scaled ground motion pair to provide the recommended suite of at least 7 analyses in which no collapse occurred.

For intensity 7, analyses did not converge for two of the 7 ground motion pairs. Two additional ground motion pairs were selected, scaled, and used to reanalyze the structure. One of these additional analyses also failed to converge. Since the spectral intensity of the segment ($S_a(\bar{T}) = 1.528$) is less than $\hat{S}_a(\bar{T})$ and fewer than 7 analyses with no collapse exist, an additional

ground motion pair was selected, scaled, and used to analyze the structure. Analysis with this pair did not produce collapse.

For intensity 8, three of the 7 ground motion record pairs produced collapse. As with intensities 6 and 7, the probability of collapse for this intensity segment is less than 0.5, therefore additional analyses are needed to produce a total of 7.

5.8 Input Response Data and Calculate Performance

Structural analysis results for each of the 8 intensity levels are input to PACT on the **Structural Analysis Results** tab. Figure 5-6 illustrates the drift input values for intensity 3, direction 1. Input includes spectral acceleration ($S_a = 0.615g$), dispersion ($\beta_m = 0.47$) and includes input for all 7 demand vectors. Peak floor accelerations are input similarly.

Floor/Story	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7
Floor 4-Roof (rad)	0.004296831	0.005795568	0.008094784	0.007021284	0.010870556	0.006369066	0.00560472
Floor 3-4 (rad)	0.018982738	0.012247952	0.019239786	0.014597783	0.013585362	0.012696919	0.016766684
Floor 2-3 (rad)	0.022711918	0.021013815	0.022532731	0.017571038	0.013793974	0.015619827	0.020303947
Floor 1-2 (rad)	0.020122184	0.021805577	0.019862269	0.014871963	0.011190591	0.014016425	0.018451987

Figure 5-6 PACT Structural Analysis Results tab with drift input for intensity 3.

Peak residual drift values are input via the **Residual Drift** tab. Figure 5-7 illustrates this input for intensity 3. The residual drift fragility information in the upper portion of the screen remains the same as in the previous assessment model developed in Chapter 4 (median value of 0.0125 and a dispersion of 0.3).

The mean annual frequency of exceedance values corresponding to each of the intensities is input via the **Hazard Curve** tab.

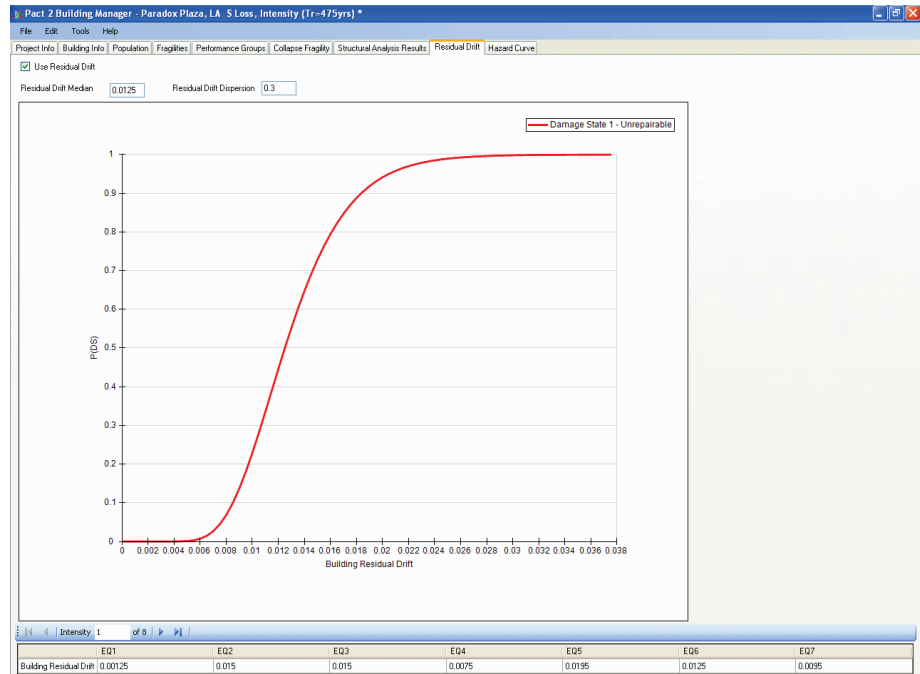


Figure 5-7 PACT Residual Drift tab input.

5.9 Review Results

PACT displays assessment results on the **Time Based Results** tab as shown in Figure 5-8, which shows annual probability of exceedance for repair cost of different amounts as well as average annual loss values. In the illustration, the average annual probability of collapse is shown in the box at the upper left hand corner of the figure as 0.000157. This is equal to a mean return period for collapse of 6,370 years. Similarly, the box below this indicates an average annual probability of 0.0051 for damage being so severe that an unsafe placard is posted on the building, equal to a mean return period of approximately 200 years.

To determine the repair cost that has a 10% probability of non-exceedance over the 30 year loan period, it is necessary to calculate the corresponding return period for such a loss. The mean return period, P_R , can be calculated as a function of the number of years in the period of interest, Y , and the desired probability of exceedance, P_{EY} , using the formula:

$$P_R = \frac{-Y}{\ln(1 - P_{EY})}$$

For this example: $Y = 30$ years, $P_{EY} = 10\% = 0.10$. Substituting and solving

$$P_R = \frac{-30}{\ln(1 - 0.1)} = 285 \text{ years}$$

The 285-year return period for the desired loss equates to an annual frequency of exceedance of 1/285 years or 0.0035 per year. For the case of Figure 5-8, with this annual probability of non-exceedance, the associated repair cost is found as \$3.8M. This represents 17.6% of the building's total replacement cost.

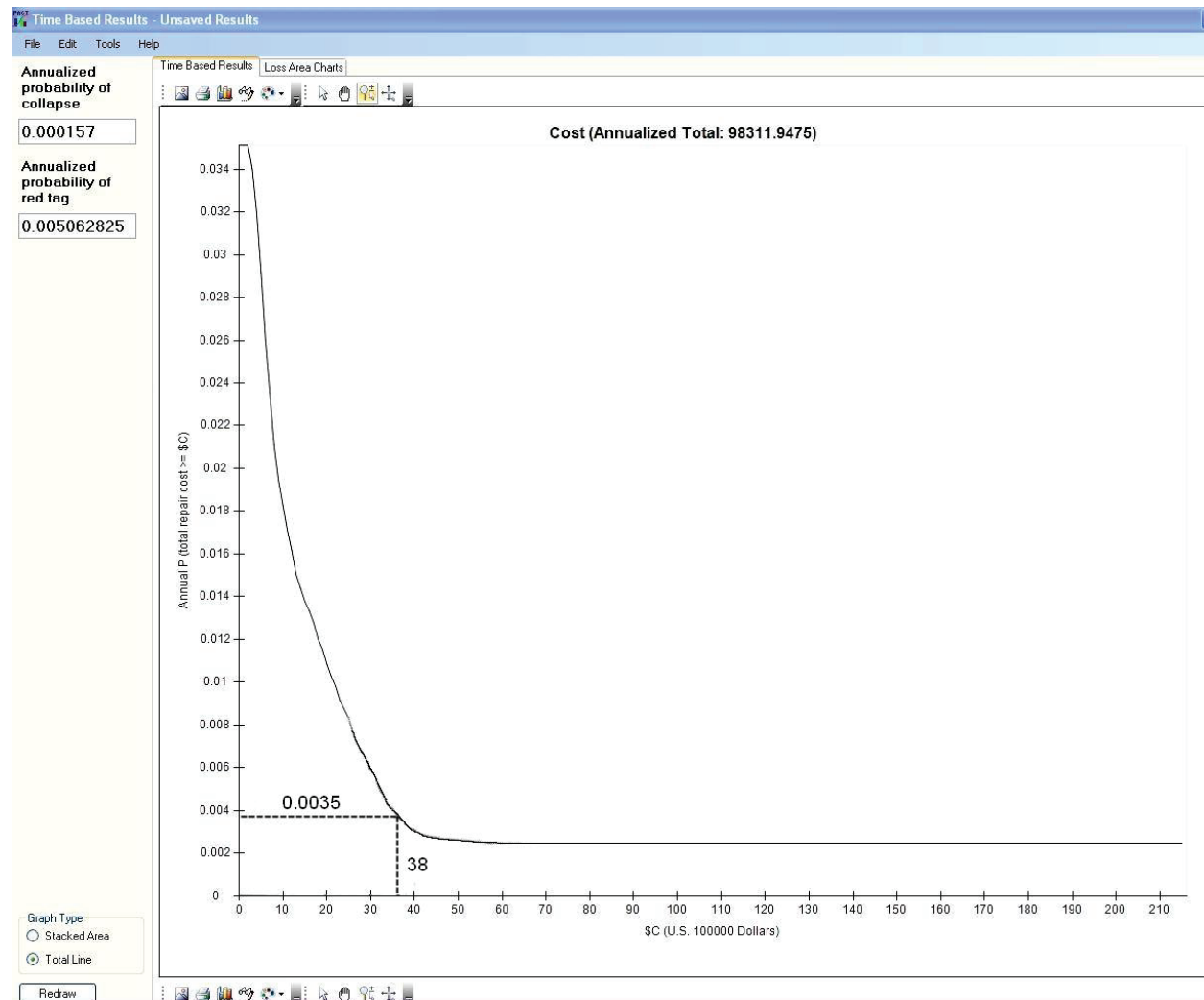


Figure 5-8 PACT Time Based Results tab showing annualized repair cost.

Chapter 6

Structural Fragility Calculation

6.1 Introduction

Volume 1, Section 3.8 presents procedures for calculation of fragility parameters for component damage states associated with limit states that can be predicted by calculation. This chapter illustrates those procedures using a sample tilt-up building comprised of a plywood diaphragm, wood-framed roofing, and reinforced concrete walls. The examples illustrate application of the procedures for ductility-limited and strength-limited damage states (ductile and brittle). The examples provide insight into the process of selecting damage states and demand parameters to characterize component performance. The following structural components and systems are addressed:

- Plywood diaphragms
- Tilt-up concrete walls
- In-plane wall to roof attachment
- Out-of-plane wall to roof attachments

By applying the procedures illustrated here, users can apply the methodology to include structures that have components for which there are no provided fragility specifications. Section 6.4 describes the procedure for entering user-defined fragility specifications into *Performance Assessment Calculation Tool* (PACT) provided in Volume 3.

Chapter 7 provides guidance on the development of nonstructural component fragility functions by calculation. Chapter 8 provides guidance on the development of consequence functions to complete the fragility specification.

6.2 Building Description

An example structure is used to illustrate the calculation of various component fragility functions. The structure is of conventional tilt-up concrete construction with a plywood roof diaphragm. Figure 6-1 is a roof plan for the structure and Figure 6-2 a cross-sectional elevation. Table 6-1 defines basic structural data.

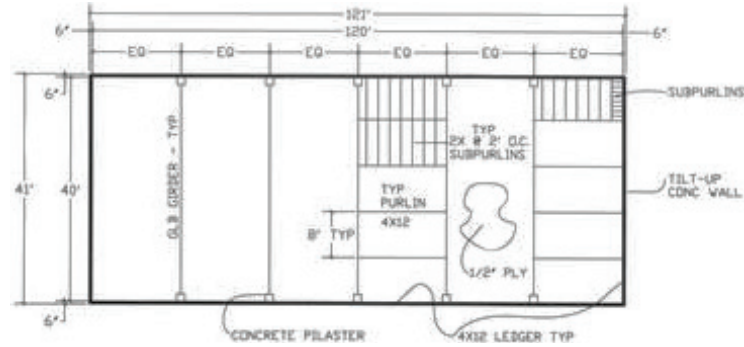


Figure 6-1 Roof plan.

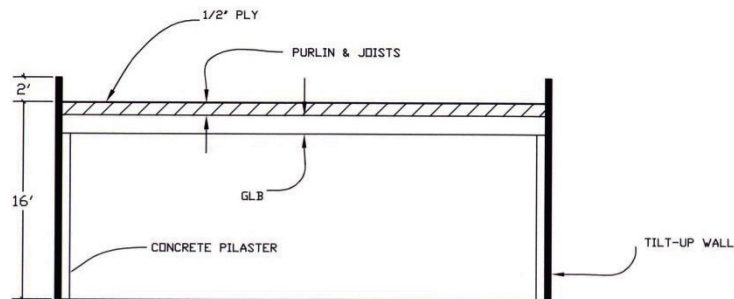


Figure 6-2 Cross-sectional elevation.

Table 6-1 Basic Building Information

Building Components	Details of Construction
Plywood diaphragm	1/2" structural I plywood Blocked and chorded Uniformly nailed 10d @ 6" panel edges
Tilt-up reinforced concrete walls	6" thick #5 @ 12" EW ASTM A615 Grade 60 reinforcement $f'_c = 4000\text{psi}$ (normal weight) Chords: 2 #5 rebar
In-plane wall to roof attachment	10d @ 6" plywood to ledger nailing 5/8" Φ anchor bolt @ 2' o.c. with 4 1/2" embedment into concrete wall
Out-of-plane wall to roof attachment	2 holdowns (12 GA) with 2 - 5/8" Φ thru bolts (purlin attachment) and 2 5/8" Φ anchor bolts (or threaded rods) with 4 1/2" embedment into concrete wall, at 8 feet on center

The building's basic lateral force-resisting components include the horizontal plywood diaphragm, which distributes seismically induced inertial loads to the walls of the building parallel to the direction of seismic action. The seismic inertial loads predominantly reflect the inertial mass of the perimeter walls normal to the direction of seismic action. The diaphragm resists seismically induced deformation by spanning horizontally to the vertical shear resisting elements (tilt-up walls) at the building perimeter. The

diaphragm exhibits fundamentally the same behavior modes in each direction of seismic demand.

Reinforced concrete walls act as shear walls to provide restraint to the diaphragm for seismic forces acting parallel to the walls. For seismic forces acting perpendicular to the walls, the walls transmit inertial reactions to the roof diaphragm and to the foundation. The attachments of the walls to the roof transfer the diaphragm end forces along the length of the in-plane walls and transfer the out-of-plane inertial wall loads into the horizontal diaphragm at discrete 8-foot intervals where tension ties (2 holdown devices) are located.

Damageable components of the building's lateral force-resisting system include:

- Plywood roof diaphragm
 - Transverse
 - Longitudinal
- Tilt-up reinforced concrete walls
 - In-plane
 - Out-of-plane
- Wall to roof attachments
 - In-plane
 - Out-of-plane

The walls and roof are attached to transfer in-plane and out-of-plane wall and diaphragm demands. The in-plane attachment (Figure 6-3) consists of a diaphragm ledger (3×8, DF#1, timber) and steel anchor bolts that are embedded into the concrete wall (5/8 inch diameter at 2 feet on center). The out-of-plane attachment consists of holdown hardware (see Figure 6-4 and Figure 6-5) attached to diaphragm sub-framing and bolted to the concrete wall in a fashion similar to that of the in-plane connection. The sub-framing is attached to the plywood diaphragm via nailing that provides a mechanism for engaging the diaphragm to resist inertial wall demands. The sub-framing includes splice detailing to maintain transfer continuity over a distance sufficient to engage an adequate number of nails between the sub-framing and the plywood.

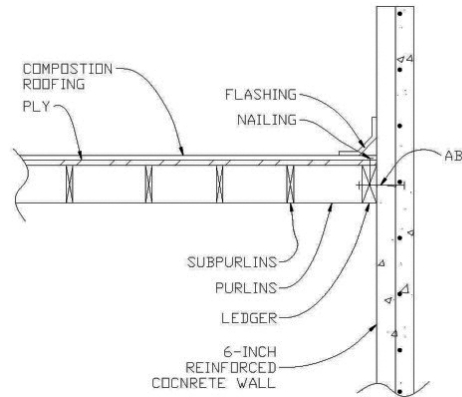


Figure 6-3 In-plane attachment.

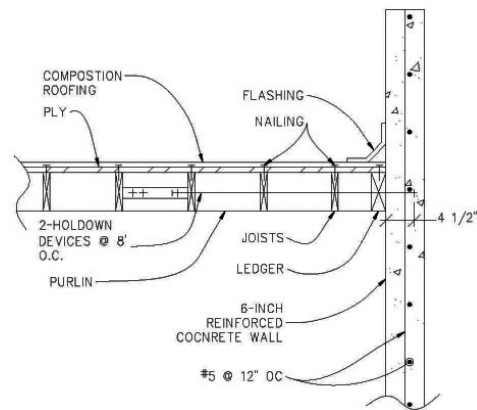


Figure 6-4 Out-of-plane attachment.

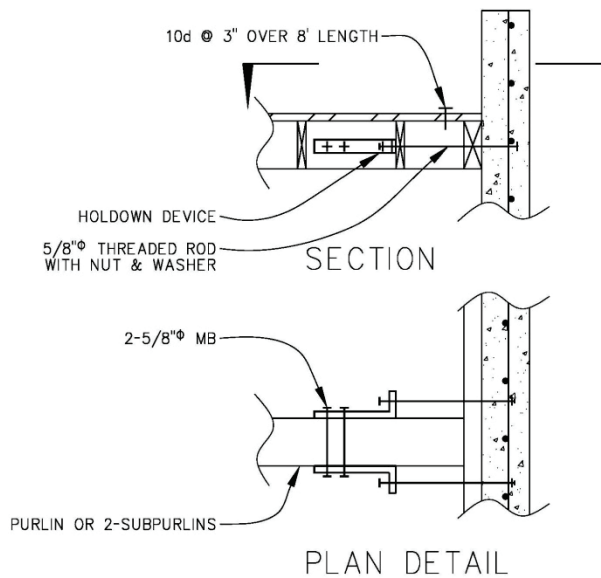


Figure 6-5 Horizontal holddown (out-of-plane) attachment.

6.3 Development of Structural Component and System Fragilities by Calculation

Volume 1, Section 3.8 presents procedures for calculating component fragility functions based on characteristics of the anticipated component limit state. The following four limit state categories are identified:

- Ductility-limited damage states
- Strength-limited damage states
- Displacement-limited damage states
- Code-based capacity damage states

Each limit state assumes a mathematical relationship between a demand parameter and the occurrence of a damage state. For each category, an estimate of the median value of the demand, θ , at which the damage state is likely to occur is analytically estimated. It is assumed that the probability of incurring damage at different values of demand is lognormally distributed with dispersion, β . The value of the dispersion is selected to reflect the variability in the following: component material strength, β_M ; the predictive equations used to derive the median demand estimate, β_D ; and the degree to which the actual construction is likely to match the construction quality, β_C , implicit in the median demand calculation. These procedures are illustrated with the generation of fragility functions for the components and systems of the example building.

6.3.1 Plywood Roof Diaphragm

The plywood roof diaphragm is considered to include composition roofing and flashing, plywood sheathing, nailing attachment to the sub-framing, and chord and collector elements.

The diaphragm can sustain damage in the following ways:

- Nail pullout at plywood panel edges or buckling of plywood panels
- Chord or collector buckling
- Chord or collector splice failure in tension

In this example, there are no collectors because the walls and diaphragm are continuously attached. The chords consist of reinforcing steel embedded in the concrete perimeter walls and are unlikely to buckle or fail given the relative vulnerability of the wood framing components. Therefore, potential damage states associated with chords or collectors are not addressed in this example.

Testing and observation of the performance of plywood diaphragm systems (Tissel, 1967) suggests damage states of substance include nail pullout and panel buckling (Figure 6-6 and Figure 6-7).

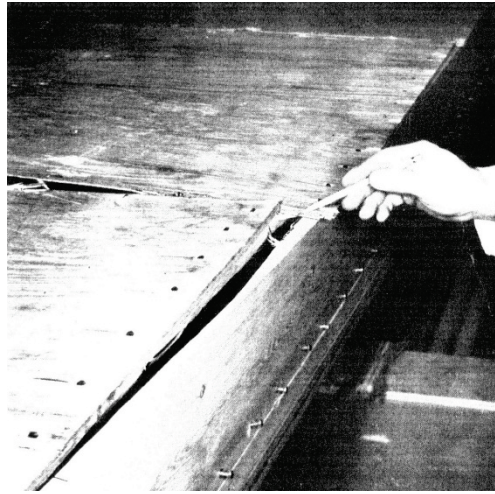


Figure 6-6 Plywood diaphragm damage (Tissel, 1967).

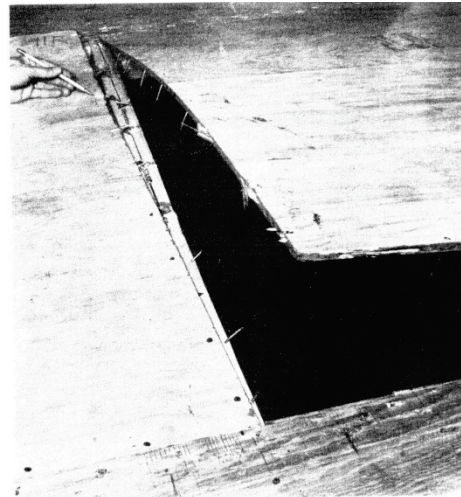


Figure 6-7 Plywood diaphragm damage (Tissel, 1967).

A fragility function for plywood diaphragm damage states consisting of nail pullout and panel buckling damage mechanisms is generated by calculation using the procedure provided in Volume 1, Section 3.8.

Anticipated horizontal diaphragm performance can be characterized using the generalized force-deformation “backbone” relationship as defined in ASCE/SEI 41-06, *Seismic Rehabilitation of Existing Buildings*, (ASCE, 2007) and as shown in Figure 6-8 below:

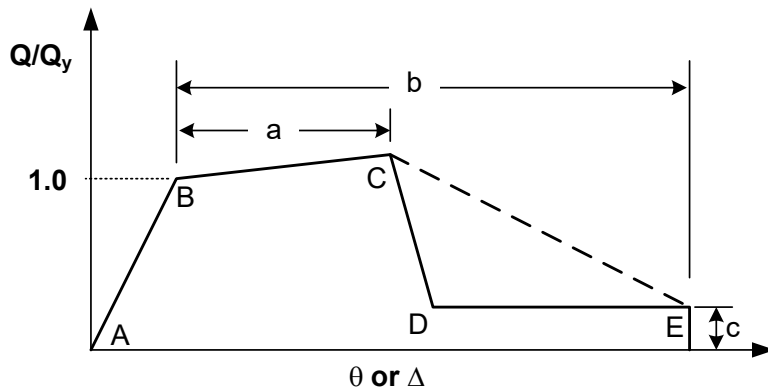


Figure 6-8 Generalized force-deformation relationship adapted from ASCE/SEI 41-06 (ATC, 2010).

Response modeling parameters a , b , and c (illustrated in Figure 6-8) are determined, according to ASCE/SEI 41-06 Table 8-4, since the subject diaphragm has a span-to-depth ratio of approximately 3 to 1 and is blocked and chorded. ASCE/SEI 41-06 also provides response values that are judged to reflect three levels of component performance: Immediate Occupancy, Life Safety, and Collapse Prevention. ASCE/SEI 41-06 Table C1-4 provides a qualitative description of the anticipated degree of damage associated with each of these response levels. For Immediate Occupancy performance, observable loosening, withdrawal of fasteners, and splitting of sheathing or framing are not anticipated. For Life Safety performance, observable withdrawal of fasteners is expected, as well as splitting of framing, sheathing, and connections. For Collapse Prevention performance, large permanent distortion of the diaphragm is expected, accompanied by extensive splitting of framing, connections, and sheathing in addition to partial nail withdrawal.

For the diaphragm system in this example, three damage states of consequence are considered. In Damage State 1 (DS1), no damage to the plywood, nailing, or framing is anticipated, but damage to the roof flashing at the wall to diaphragm interface is expected. This damage will require removal and reinstallation of the flashing. Additionally, tearing of roofing materials at this interface can be expected.

In the backbone curve:

Δ = Total elastic and plastic deformation

Δ_y = Displacement at effective yield strength

The ratio of total displacement to yield displacement is frequently characterized as the displacement ductility ratio, μ . This characterization of

component performance corresponds to the ductility-limited damage state category previously discussed.

Using the ASCE/SEI 41-06 backbone curve and the Immediate Occupancy (IO) and Life Safety (LS) acceptability limits of Δ/Δ_y equal to 1.8 and 3.3, respectively, Damage State 1 (DS1) can be inferred to occur after the IO acceptability limit has been exceeded but before the LS acceptability limit is reached. Thus, DS1 will be assumed to occur at a $\Delta/\Delta_y = 2.5$, as shown in Figure 6-9.

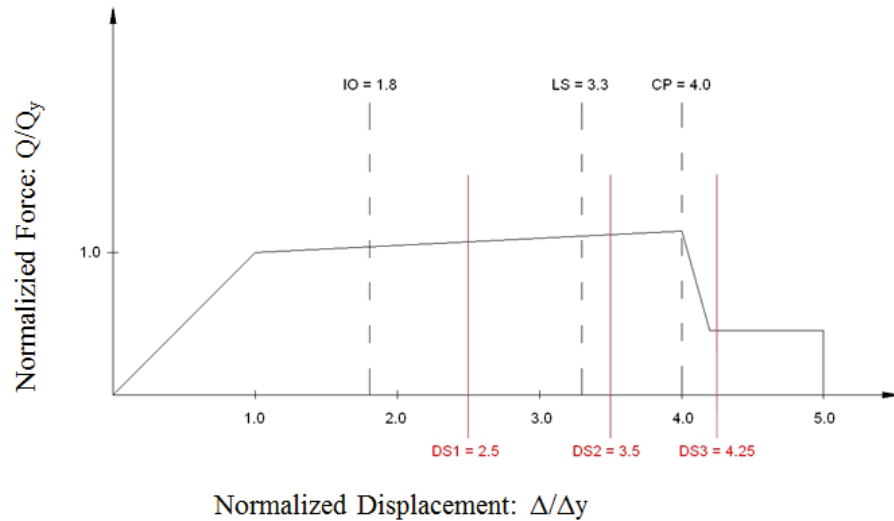


Figure 6-9 Determining plywood diaphragm damage states.

As diaphragm deformations increase, damage requiring repair of nailing, sheathing, and framing will occur. The onset of this damage will be defined as Damage State 2 (DS2) and be assumed to occur at a deformation level of $\Delta/\Delta_y = 3.5$ (slightly greater than the LS acceptability limit).

As diaphragm deformations continue further, a level of damage will be reached at which complete resheathing and reframing over approximately 25% of the diaphragm span nearest to the in-plane walls will be required. This damage state is defined as Damage State 3 (DS3) and is assumed to occur at $\Delta/\Delta_y = 4.25$. This corresponds to a deformation slightly beyond the Collapse Prevention acceptability limit yet short of the complete loss of residual component strength.

The five-step procedure presented in Volume 1, Section 3.8 characterizing ductility-limited damage states is illustrated below.

Step 1. Calculate the median value, θ , and dispersion, β , for the onset of yield of the element using Volume 1 Equation 3-1:

$$\theta = C_q e^{(2.054\beta_I)} \phi R_N$$

The yield strength of a plywood diaphragm can be determined using the load resistance factor design (LRFD) procedures contained in ANSI/AF&PA SDPWS-2005, *Special Design Provisions for Wind and Seismic* (AF&PA, 2005b). For a 1/2-inch thick, Structural I plywood, blocked diaphragm with 10d common nails spaced at 6 inches along diaphragm boundaries and at all panel edges (with 2 inch wide sub-framing), Table 4.2A of ANSI/AF&PA SDPWS-2005 provides a nominal unit shear capacity, v_s , of 640 plf. For LRFD, a resistance factor, ϕ_D , with a value of 0.8 is applied to this value for seismic demands.

Thus $\phi R_N = 0.8(640) = 512$ plf

C_q is a coefficient to adjust the median value based on sensitivity of the behavior mode to construction quality. For this example, C_q will be taken as 1.0.

The dispersion parameter, β_I , is composed of three parts intended to reflect uncertainty associated with the onset of yield and is calculated as follows:

$$\beta_I = \sqrt{\beta_D^2 + \beta_M^2 + \beta_C^2}$$

where:

β_D = variability of the predictive equation used to calculate component yield

β_M = variability in material properties

β_C = variability associated construction quality and care

For this example, β_D is taken as 0.1 to reflect the relatively complex behavior of plywood, nails, and sub-framing, β_M , is taken as 0.2 (Volume 1, Table 3-4) to reflect the variability of visually graded lumber products and β_C will be taken as 0.1 to reflect an average degree of construction quality control and a moderate sensitivity to construction quality. Therefore,

$$\beta_I = \sqrt{(0.1)^2 + (0.2)^2 + (0.1)^2} = 0.24$$

The median value, θ , for the onset of yield is calculated to be:

$$\begin{aligned} \theta &= (1.0) e^{(2.054 \times 0.24)} (512) \\ &= 1.64 (512) = 838 \text{ plf} \end{aligned}$$

Step 2. Calculate the median deformation of the element, δ_y , at the onset of yield, using elastic deformation analysis under the applied median yield load.

A median estimate of the midspan deformation, δ_y , at yield can be calculated using ANSI/AF&PA SDPWS-2005 Equation 4.2.1 as follows:

$$\delta_y = \frac{5v_{ye}L^3}{8EA W} + \frac{0.25v_{ye}L}{1000G_a} + \sum \frac{\Delta_c X}{2W}$$

where:

v_{ye} = median estimate of diaphragm strength at yield: 838 plf

L = diaphragm span (ft)

E = diaphragm chord modulus of elasticity (psi)

A = diaphragm chord cross sectional area (in²)

W = diaphragm width (ft)

G_a = diaphragm effective shear stiffness including nail slip and panel shear deformation (kips/inch)

Δ_c = diaphragm chord slip at yield

X = distance from chord splice to nearest support (ft)

For the diaphragm transverse direction:

L = 120 ft

E = 29,000,000 psi (2- #5 rebar)

A = 0.62 in²

W = 40 ft

v_{ye} = 838 plf

G_a = 24.0 kips/inch

$\Delta_c X$ = Assumed to be zero for this example

Therefore,

$$\delta_y = \frac{(5)(838)(120)^3}{(8)(29,000,000)(0.62)(40)} + \frac{(0.25)(838)(120)}{1000(24)} + 0$$

$$\delta_y = 1.26 + 1.05 + 0$$

$$\delta_y = 2.3 \text{ inches}$$

Note that the equation used to estimate diaphragm mid-span deflection at yield is based on a uniformly distributed loading pattern over the span length. Such a distribution may not be a good approximation of the likely pattern of diaphragm loading for a flexible diaphragm system (ASCE/SEI 41-06, Commentary to Section 3.2.4). To account for the uncertainty associated with the use of this selected deformation formulation, an adjustment to the yield dispersion, β_I , is made in Step 5 below.

Step 3. For DS1, $\mu = \Delta/\Delta_y = 2.5$ and therefore this damage state behavior mode is classified as “moderate ductility.” For DS2, $\mu = 3.5$ and is also classified as “moderate ductility.” For DS3, $\mu = 4.25$ which corresponds to “high ductility.”

Step 4. The median displacement estimates for each damage state are calculated with $\theta = \mu\delta_y$.

Step 5. The dispersion associated with each of the damage states is given by Volume 1, Equation 3-4:

$$\beta = \sqrt{\beta_I^2 + 0.16} \leq 0.6$$

As noted in Step 2, the formulation used to estimate the median value of diaphragm deflection at yield does not reflect a good approximation of the distribution of inertial loading. The added uncertainty of using this formulation will be addressed by modification of the dispersion. The previously calculated β_I (see Step 1) is recalculated using a β_D value of 0.2 in lieu of 0.1.

The resulting value of β_I is

$$\beta_I = \sqrt{(0.2)^2 + (0.2)^2 + (0.1)^2} = 0.3$$

using the revised β_I value,

$$\beta = \sqrt{(0.3)^2 + 0.16} = 0.5$$

Table 6-2 summarizes the damage states and median mid-span displacement estimates determined by calculation for the transverse span of the plywood diaphragm governed by nail pullout and panel buckling behavior limiting mechanisms. Figure 6-10 plots the resulting fragility functions for these three damage states, assuming lognormal distributions.

Table 6-2 Damage State Descriptions for Plywood Roof Diaphragm - Transverse

Damage State	Damage Description	Repair Description	Displacement (in)	Dispersion
DS1	Tearing of roofing materials and flashing at wall supports. No damage to plywood and framing below.	Remove existing flashing along wall. Remove 4-foot width of roofing at wall. Install new roofing and flashing.	5.8	0.5
DS2	In addition to DS1 damage, nail pull out, framing splitting and plywood tearing occurs.	Extend DS1 repairs to an 8-foot width, remove damaged nails and install new nails where no splitting of framing occurs (25% of nails over 8 foot width of diaphragm along wall). Remove and replace plywood and framing including ledgers at split framing or damaged plywood (25% of 8 foot width of diaphragm along wall).	8.1	0.5
DS3	In addition to damage described for DS1 and DS2, plywood panels pull free of sub-framing and framing splits over approximately 25% of the diaphragm span at each diaphragm support.	Remove and replace roofing, flashing, plywood, framing (girder not replaced) over 25% of diaphragm span and full depth of wall at each diaphragm support.	9.8	0.5

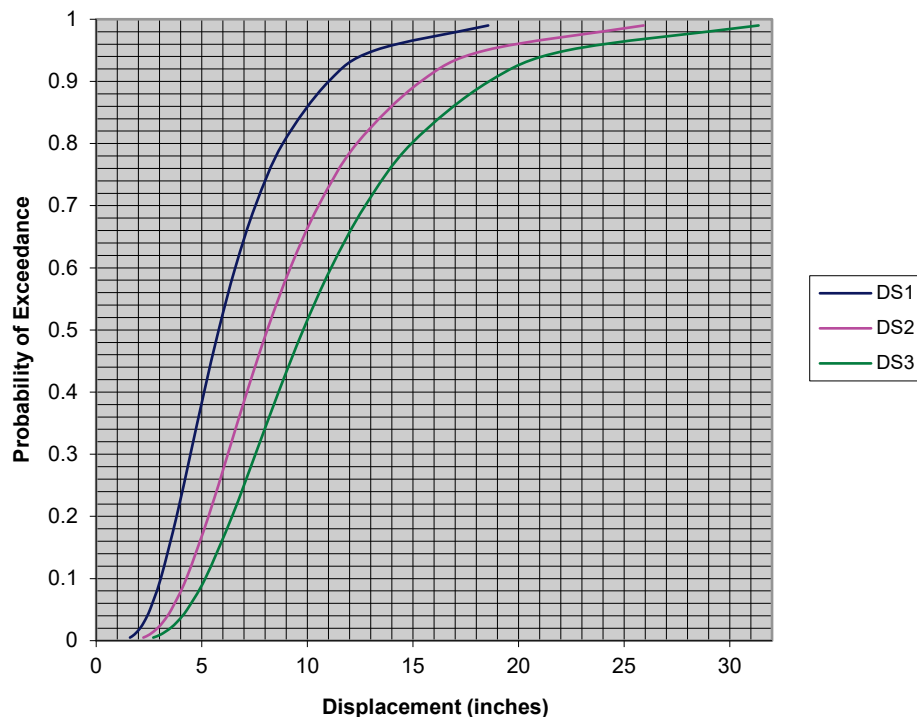


Figure 6-10 Fragility functions for plywood diaphragm in transverse direction.

The demand parameter used with these fragilities is the mid-span diaphragm displacement, Δ . Values for this parameter should be calculated from a response history analysis using a nonlinear characterization of the diaphragm construction.

6.3.2 Tilt-Up Walls

The six-inch thick, reinforced concrete walls are subjected to in-plane and out-of-plane seismic demands, which induce fundamentally different types of performance. In-plane performance can be adequately represented by the provided fragility specifications for low aspect ratio ($h/l < 1.0$) concrete walls (B1044.001 through B1044.083). These specifications reflect the performance characteristics of low aspect ratio concrete walls for which the relative capacity of the wall-to-foundation connections are adequate to develop the shear and overturning capacity of the wall without a pre-emptive failure of the connection. For this example, it has been assumed that the panel base anchorages are adequate to provide this condition. For buildings where this is not the case, fragility specifications for wall anchorages should be developed using the procedures of Volume 1, Section 3.8.

Out-of-plane seismic demands on slender concrete walls can also produce damage. When walls are subjected to out-of-plane accelerations that exceed the wall's flexural and shear resistance, cracking will occur. Initially, the cracking will require cosmetic repairs to interior and exterior finishes. At higher levels of acceleration, flexural reinforcement will yield and larger cracks will result, requiring patching or epoxy injection to reconstitute the wall's weather protection. At yet larger accelerations, flexural yielding will lead to spalling and degradation that when coupled with the effects of the supporting weight of the wall above can result in wall collapse.

In addition to the effects of acceleration on out-of-plane wall behavior, large deformations of the roof system can induce significant flexural demands in the attached walls. These demands produce wall flexure due to the eccentricity of the wall weight from its vertical support at grade. These effects are generally described as P- Δ effects.

Damage will initiate in the wall at the location where flexural demand is a maximum. Maximum flexural demand can be determined by analysis, by modeling representative wall panels as nonlinear multi-segment beam elements, extending from the ground to the roof diaphragm, and by distributing the wall panel mass along these elements. Response history analysis will compute the moment demand along the wall at each time step

and permit prediction of a maximum value of moment demand for each analysis.

The moment curvature relationship for the tilt-up wall subject to out-of-plane flexure can be idealized as illustrated in Figure 6-11.

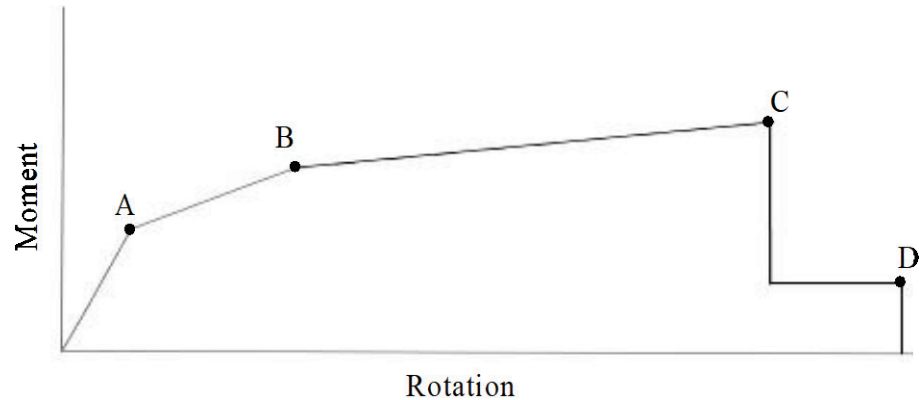


Figure 6-11 Idealized moment-rotation relationship.

In order to construct fragility curves following the procedures of Volume 1, Section 3.8, the median value of strength and dispersion have to be calculated. The following example illustrates this calculation.

In order to fulfill Volume 1, Equation 3-1, the component design strength needs to be calculated in accordance with an appropriate industry standard. To accomplish this, the moment values associated with the control points of the curve can be approximated as follows:

Step 1. Establish moment values associated with the control points A, B, and C, in the moment-rotation relationship of Figure 6-11.

Point A: Cracking Moment

ACI 318-05, *Building Code Requirements for Structural Concrete and Commentary*, (ACI, 2005) provides the following formula for cracking moment:

$$M_{cr} = \frac{f_r I_g}{y_t}$$

where:

f_r = modulus of rupture and for normal weight concrete can be taken as $7.5\sqrt{f'_c}$

I_g = gross moment of inertia of section (neglecting reinforcing)

y_t = distance from centroidal axis of section to tension face (neglecting reinforcing)

For the tilt-up wall section

$$f_r = 7.5\sqrt{4000} = 474.3 \text{ psi}$$

$$I_g = \frac{12(6)^3}{12} = 216 \text{ in}^4$$

$$y_i = 3.0 \text{ in}$$

Thus,

$$M_{cr} = \frac{(474.3)(216)}{3.0} = 34149.6 \text{ lb-in}$$

or

$$M_{cr} = 2846 \text{ lb-ft}$$

Point B: Yield Moment

The yield moment can be calculated using ACI 318-05. The yield moment can be calculated as

$$M_y = A_s a_u d$$

where:

A_s = Area of longitudinal reinforcement

$$a_u = f_y \left(\frac{1 - 0.59q}{12000} \right)$$

$$q = \frac{A_s f_y}{bd f'_c}$$

d = distance from extreme compression fiber to centroid of longitudinal steel

f_y = reinforcement yield stress

f'_c = concrete strength

b = width of section

Substituting

$$A_s = 0.31 \text{ in}^2 \text{ (#5@12 inches)}, f_y = 60,000 \text{ psi}, f'_c = 4,000 \text{ psi}, b = 12 \text{ in}, d = 3 \text{ in.}$$

$$a_u = \frac{60,000}{12,000} \left(1 - (0.59) \left(\frac{0.31(60,000)}{(12)(3)(4,000)} \right) \right)$$

$$a_u = 4.62$$

$$M_y = (0.31)(4.62)(3) = 4.30^{k-1} \text{ or } M_y = 4297$$

Point C: Peak Moment

The peak moment is estimated to occur at a rotation that is approximately 3 to 4 times that which produced M_y . The peak moment can be assumed to be 120% of the yield moment, $M_B = 5,156 \text{ lb-ft}$.

Step 2. Establish damage state descriptions.

The following damage states are considered:

- DS1: Onset of flexural cracking requiring only cosmetic repair (minor patching and painting)
- DS2: Post-yield flexural cracking including cracking and spalling requiring patching, possibly epoxy injection, and painting. Figure 6-12 illustrates a damage state similar to DS2.
- DS3: Significant spalling and degradation leading to partial wall collapse requiring removal and reconstruction.

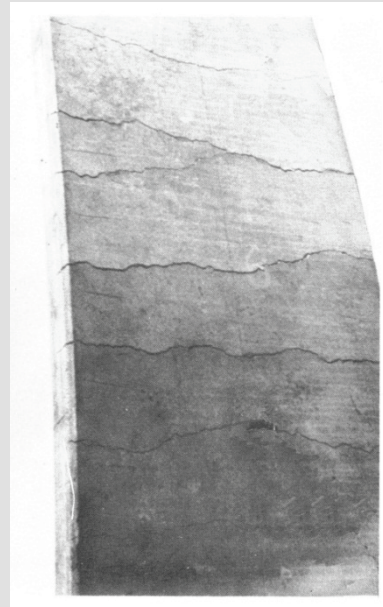


Figure 6-12 Photo showing DS2 level cracking (Selna, 1981).

Step 3. Calculate median strength and dispersion for Damage State 1

For DS1, the demand will be taken as the moment which is 10% of the difference between points A and B or

$$M_{DS1} = 2,846 + 0.1(4,297 - 2,846)$$

$$M_{DS1} = 2,991 \text{ lb-ft}$$

Define this as a strength-limited damage state characterized by ductile performance (flexure).

Determine the median strength as

$$\theta = C_q e^{(2.054 \beta_1)} \phi R_n$$

From ACI 318-05:

$\phi = 0.9$ for tension controlled actions

$$\phi R_n = \phi M_{DS1} = 0.9(2,991) = 2,692 \text{ lb-ft}$$

$$\beta_I = \sqrt{\beta_D^2 + \beta_M^2 + \beta_C^2}$$

For the DS1 estimate (cracking strength), select

$$\beta_D = 0.10, \beta_M = 0.12, \beta_C = 0.10$$

$$\beta_I = \sqrt{(0.1)^2 + (0.12)^2 + (0.1)^2} = 0.185 \text{ or } \beta_I = 0.2$$

$$C_q = 1.0$$

$$\theta = (1.0)e^{2.054(0.2)}(2,692)$$

$$\theta = 4,060 \text{ lb-ft}$$

Assign a dispersion

$$\beta = \sqrt{\beta_I^2 + 0.16} \text{ where } \beta_I \text{ is defined above}$$

$$\beta = \sqrt{(0.2)^2 + 0.16} = 0.45 \text{ or } \beta = 0.5$$

For DS1, $\theta = 4,060 \text{ lb-ft}$, $\beta = 0.5$

Step 4. Calculate median strength and dispersion for Damage State 2

For DS2, the demand will be taken as 25% of the difference between points B and C' or

$$M_{DS2} = 4,297 + 0.25(5,156 - 4,297) = 4,511 \text{ lb-ft}$$

Similar to DS1, this will be defined as a strength-limited damage state characterized by ductile performance (flexure).

Determine the median strength as

$$\theta = C_q e^{(2.054\beta_I)} \phi R_n$$

$$\phi R_n = \phi M_{DS2} = 0.9(4,511 \text{ lb-ft}) = 4,060 \text{ lb-ft}$$

For the DS2 strength estimate (post yield), select

$$\beta_D = 0.05, \beta_M = 0.12, \beta_C = 0.10$$

$$\beta_I = \sqrt{(0.05)^2 + (0.12)^2 + (0.10)^2} = 0.164 \text{ or } \beta_I = 0.2$$

$$C_q = 1.0$$

$$\theta = (1.0)e^{(2.054)(0.2)}(4,060) = 6,122 \text{ lb-ft}$$

Assign a dispersion:

$$\beta = \sqrt{(0.2)^2 + 0.16} = 0.45 \text{ or } \beta = 0.5$$

For DS2: $\theta = 6,122$ lb-ft, $\beta = 0.5$

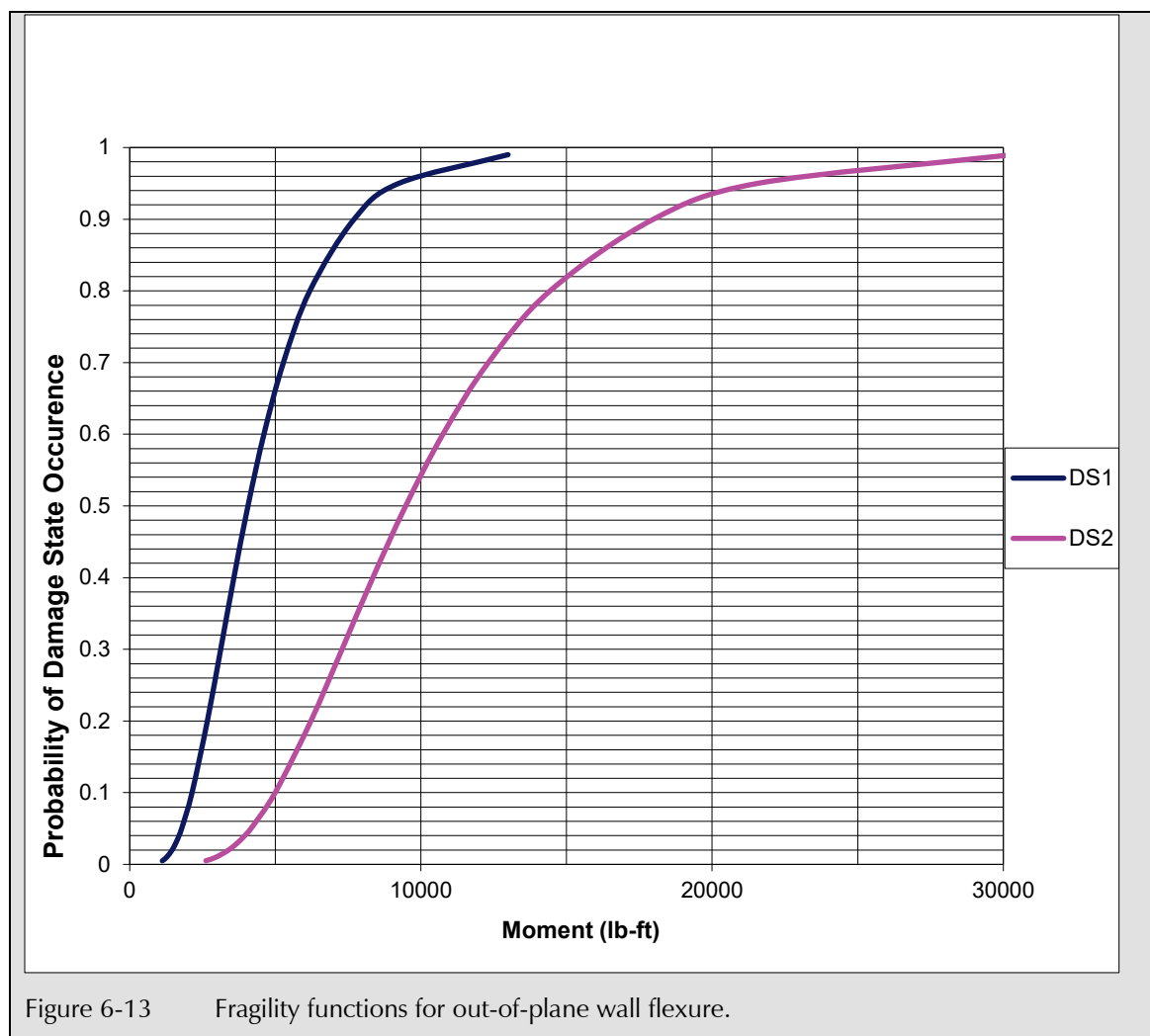
Step 5. Calculate median strength and dispersion for Damage State 3

The occurrence of DS3 will be considered as a form of partial collapse and will have a collapse fragility associated with it, based on incremental dynamic analysis. This procedure is not illustrated here.

Table 6-3 summarizes the out-of-plane damage states and demand parameters for the longitudinal tilt-up concrete walls. The walls are subjected to out-of-plane acceleration and displacement effects that produce a wall flexure behavior mechanism. Demands, in the form of peak bending moment, are predicted by modeling individual wall panels as strings of nonlinear beam elements with distributed mass, extending from the building base to the roof diaphragm. Figure 6-13 presents a plot of the fragility functions for damage states DS1 and DS2.

Table 6-3 Damage State Descriptions for Tilt-Up Walls—Out-of-Plane

Damage State	Damage Description	Repair Description	Bending Moment (lb-ft)	Dispersion
DS1	Onset of flexural cracking requiring cosmetic repair	Over 4 foot distance at mid-height of wall grout patch surface and repaint wall. Work occurs over middle third of diaphragm span.	4,060	0.5
DS2	Post yield flexural cracking with light spalling, requiring patching, possible epoxy injection, and painting.	In addition to work done for DS1, over 6-foot distance at mid-height of wall, patch spalls, epoxy inject 2 cracks (20 feet long each) and paint wall. Work occurs over middle third of diaphragm span.	6,122	0.5
DS3	Significant spalling and degradation leading to partial wall collapse.	Determined using incremental dynamic analysis and predicted by a building collapse fragility function.	-	-



6.3.3 Wall to Roof Attachments

As previously described, the wall and roof are attached to transfer in-plane and out-of-plane wall and diaphragm demands. Separate attachments serve to resist demands acting in and out of the plane of the perimeter wall. Damage can occur to each type of these attachments. Fragility functions which were derived analytically will be developed for each of these attachments in the sections to follow.

6.3.3.1 In-Plane Attachment – Failure at Ledger Bolting

Figure 6-3 illustrates the in-plane wall attachment detail. Attachment components include plywood nailing to the ledger and ledger bolting to the concrete wall. Nailing performance was previously addressed as part of the fragility specification for the plywood diaphragm. The ledger bolting system has four basic behavior modes that can result in damage. As identified in

ANSI AF&PA *National Design Specification for Wood Construction* (AF&PA, 2005a) the four potential limit states are:

- Fastener bearing failure in main or side member
- Fastener rotation failure without bending
- Fastener plastic hinge failure in main or side member
- Fastener plastic hinge failure in main and side member

The *National Design Specification for Wood Construction* provides LRFD design equations for each of these modes. The lowest value obtained from the yield limit equations is listed in *National Design Specification for Wood Construction* Table 11E.

These four limit states assume that system behavior is governed by the wood or bolt components. This requires adequate anchorage of the bolt into the concrete to preclude a preemptive failure of the concrete anchorage. This requires at least six inches of anchor embedment. Recognizing that only 4.5 inches of embedment has been provided in the example building, additional limit states associated with bolt and concrete behavior need to be considered. This will be done after investigating the potential limit states for the wood/bolt interface.

In this example, the wood/bolt capacity is limited by fastener plastic hinge failure in main and side member. This capacity is given by the formula:

$$Z = \frac{D^2}{R_d} \sqrt{\frac{2F_{em}F_{yb}}{3(1 + R_e)}}$$

where:

$$D = 0.625 \text{ inch}$$

$$F_{em} = \text{Dowel bearing strength in concrete} = 7500 \text{ psi}$$

$$F_{yb} = \text{Dowel bending yield strength} = 45,000 \text{ psi}$$

$$F_{es} = \text{Dowel bearing strength in wood} = 5,600 \text{ psi (G = 0.5)}$$

$$R_d = 3.2 K_\theta$$

$$R_e = \frac{F_{em}}{F_{es}}$$

$$K_\theta = 1 + 0.25 \left(\frac{\theta}{90} \right)$$

$$\theta = \text{angle between direction of grain and application of load (for this example, loading is parallel to the grain and therefore 0)}$$

Substituting the numerical values yields:

$$Z = \frac{(0.625)^2}{3.2} \sqrt{\frac{2(7500)(45,000)}{3(1+1.34)}} = 1197 \text{ pounds}$$

Damage in this mode consists of localized crushing of the ledger at the bolt head, bolt bending displacement and the onset of wood crushing at the bolt/concrete interface.

This force value can be converted to an LRFD capacity using *National Design Specification for Wood Construction* Table N1 and Table N2.

$$K_F Z = \phi R_n$$

where K_F is given in *National Design Specification for Wood Construction* Table N1 as $(2.16 / \phi)$ for all connections and ϕ is given in Table N2 as 0.65 for all connections. Yielding:

$$\phi R_n = \left(\frac{2.16}{0.65}\right)(1200) = 3,988 \text{ lb}$$

Damage associated with this limit state is severe lateral distortion of the bolt coupled with significant crushing and widening of the hole in the wood ledger through which the bolt passes. Repair of this damage requires installation of new bolts (post-installed) in new holes. In some locations, replacement of the ledger may be necessary due to ledger splitting.

Development of a fragility function to reflect this damage state is illustrated in the following steps:

Step 1. Define this as a strength-limited damage state characterized by ductile performance.

Determine the median strength as:

$$\theta = C_q e^{(2.054\beta_I)} \phi R_n$$

where $\phi R_n = 3,988 \text{ lb}$ as determined above.

$$\beta_I = \sqrt{\beta_D^2 + \beta_M^2 + \beta_C^2}$$

For the dispersions, select,

$$\beta_D = 0.10, \beta_M = 0.20, \beta_C = 0.10$$

$$\beta_I = \sqrt{(0.10)^2 + (0.20)^2 + (0.10)^2} = 0.24$$

$$C_q = 1.0$$

$$\text{Therefore, } \theta = 1.0 e^{(2.054)(0.24)} (3,988 \text{ lb}) = 6,549 \text{ lb}$$

Step 2. Assign a dispersion:

$$\beta = \sqrt{(\beta_1)^2 + 0.16}$$

$$\beta = \sqrt{(0.24)^2 + 0.16} = 0.47 \text{ or } \beta = 0.5$$

Table 6-4 summarizes the fragility data for in-plane damage to the ledger/bolt components. Figure 6-14 plots this fragility function.

Table 6-4 Damage State Description for Ledger to Bolt Wall Attachment—In-Plane

Damage State	Damage Description	Repair Description	Bolt Force (lbs)	Dispersion
DS1	Severe lateral bolt distortion and wood crushing at bolt with some ledger splitting	Install new epoxy anchors into ledger & concrete wall. Replace 20% of ledgers.	6,549	0.5

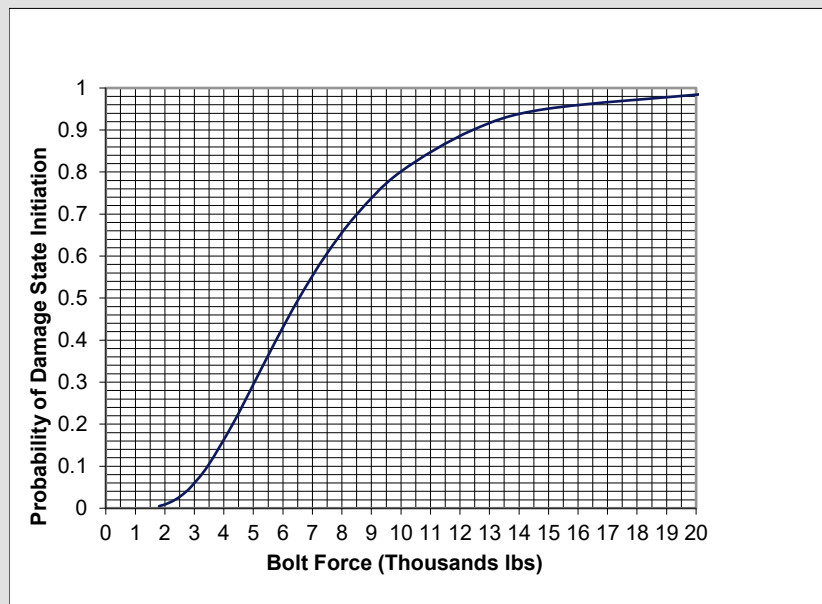


Figure 6-14 Fragility function for in plane ledger to wall connection.

6.3.3.2 In-Plane Attachment – Failure at Bolt/Concrete Interface

The preceding fragility function assumes that damage only occurs to the wood ledger and bolt system. Damage may also occur to the bolt/concrete interface due to limited anchor bolt embedment. ACI 318-05 Appendix D specifies design equations for this behavior. The following strength limit states are considered:

- Steel strength of anchor in shear
- Concrete breakout strength of anchor in shear
- Concrete pryout strength of anchor in shear

The median estimate of strength associated with each of these potential limit states will be evaluated and the lowest value will be selected for fragility function development.

Steel Strength of Anchor in Shear. For a cast-in-place headed stud anchor, ACI 318-05 Appendix D provides the following capacity:

$$V_{sa} = n A_{se} f_{uta}$$

where n is the number of anchors in a group, taken as 1 for this example, A_{se} is the effective cross section of the anchor, 0.307 in² for a 5/8 inch diameter stud anchor, and f_{uta} is the tensile strength of anchor, taken as 58 ksi.

Yielding:

$$V_{sa} = (1)(0.307)(58,000) = 17,806 \text{ lbs}$$

Concrete Breakout Strength of Anchor in Shear. If it is assumed that anchor bolts will be placed no closer than 12 inches from the edge of the tilt-up panel, ACI 318-05 Appendix D provides the following capacity:

$$V_{cb} = \frac{A_{vc}}{A_{vco}} (\psi_{ed})_v (\psi_c)_v V_b$$

where:

$$A_{vc} = (2)(1.5)(C_{ai})h_a$$

with:

$$C_{ai} = \text{edge distance} = 12 \text{ inches}$$

$$h_a = \text{wall thickness} = 6 \text{ inches}$$

$$A_{vc} = (2)(1.5)(12)(6) = 216 \text{ in}^2$$

$$A_{vco} = 4.5(C_{ai})^2 = 4.5(12)^2 = 648$$

$$(\psi_{ed})_v = 1.0 \text{ for } C_{a2} > 1.5 C_a, C_{a2} = 24 + 5 = 29$$

$$(\psi_c)_v = 1.4 \text{ for no cracking at service load levels}$$

$$V_b = 7 \left(\frac{l_e}{d_0} \right)^{0.2} (\sqrt{d_0}) (\sqrt{f'_c}) (C_{ai})^{1.5}$$

with:

$$l_e = h_{eff} = 4.5 - 0.31 = 4.2 \text{ inches}$$

$$d_0 = \text{anchor diameter} = 0.625 \text{ inches}$$

$$V_b = 7 \left(\frac{4.2}{0.625} \right)^{0.2} (\sqrt{0.625}) (\sqrt{4,000}) (12)^{1.5} = 12,047 \text{ lbs}$$

$$\text{Therefore } V_{cb} = \left(\frac{216}{648}\right)(1.0)(1.4)(12,047) = 5,622 \text{ lbs}$$

Concrete Pryout Strength of Anchor in Shear. ACI 318-05 Appendix D, provides the following pryout capacity:

$$V_{cb} = k_{cp} N_{cb}$$

where:

$$k_{cp} = 2.0 \text{ for } h_{eff} \geq 2.5$$

$$N_{cb} = \frac{A_{Nc}}{A_{Nco}} (\psi_{ed})_N (\psi_c)_N (\psi_{cp})_N N_b$$

with:

$$A_{Nc} = A_{Nco} = 9(h_{eff})^2 = 9(4.2)^2 = 158.8 \text{ in}^2$$

$$(\psi_{ed})_N = 1.0 \text{ for } C_a \geq 1.5h_{eff}$$

$$(\psi_c)_N = 1.25 \text{ for cast-in-place anchors}$$

$$(\psi_{cp})_N = 1.0 \text{ for cast-in-place anchors}$$

$$N_b = k_c \sqrt{f'_c} (h_{eff})^{1.5}$$

$$k_c = 24 \text{ for cast-in-place anchors}$$

$$N_b = 24\sqrt{4,000}(4.2)^{1.5} = 13,065 \text{ lbs}$$

$$N_{cb} = \frac{158.8}{158.8} (1.0)(1.25)(1.0)(13,065) = 16,331 \text{ lbs}$$

$$V_{cp} = 2.0(16,331) = 32,662 \text{ lbs}$$

To determine the governing strength, the median strength estimate for each potential limit state must be determined and compared. This can be done using Volume 1, Equation 3-1 for ductile modes and Volume 1, Equation 3-2 for brittle modes.

$$\theta_{ductile} = C_q e^{(2.054\beta)} \phi R_n$$

$$\theta_{brittle} = C_q e^{(2.81\beta)} \phi R_n$$

Note that ACI 318-05 Appendix D requires that in regions of high seismic risk the shear strength shall be taken as $0.75\phi V_n$, thus

$\phi R_n = (0.75)(0.75)V_n$. Table 6-5 summarizes this calculation and the corresponding median strength estimates for $C_q = 1.0$ and $\beta_I = 0.38$

Table 6-5 Median In-Plane Limit State Strengths for Anchor Bolt

Limit State	ϕR_n (lbs)	Failure Category	Strength (lbs)
Steel strength of anchor in shear	10,016	Ductile	18,548
Concrete breakout strength of anchor in shear	3,162	Brittle	7,346
Concrete pryout strength of anchor in shear	18,372	Brittle	42,684

The limit state with the lowest estimated median strength is the concrete breakout mode. The damage associated with this limit state is the breakout and spalling of the concrete at the ends of the panels.

Note that for bolts located away from the panel edges, the strength of the anchor in shear will produce the lowest estimate of median strength among the three limit states. Its estimated capacity is sufficiently greater than that of the strength associated with the limit state for the wood/bolt components (18,548 lbs vs. 6,549 lbs), thus it can be judged unlikely to occur.

Comparison of the median strength estimate of the in-plane wall attachment (ledger/bolt) of 6,549 lbs to the median strength estimate of bolts embedded at the panel edges (7,346 lbs), suggests that there is uncertainty as to which mode will actually occur. It is possible to treat these as two separate sequential damage states, or alternatively, as mutually exclusive damage states with a common median value, taken as the average of 6,549 lbs and 7,346 lbs.

To utilize the in-plane anchorage fragility, it is necessary to extract the anchor bolt force from the analysis. This can be done by dividing the diaphragm edge shear by the number of bolts.

6.3.3.3 Out-of-Plane Attachment

Figure 6-3 and Figure 6-4 illustrate the out-of-plane attachment of the roof to the wall. This attachment consists of two holdown devices fabricated from 12-gauge steel spaced at 8 feet on center. The devices are bolted together through a purlin at the transverse walls and through a doubled subpurlin along the longitudinal walls. Each device is also attached to a threaded rod that is embedded into the perimeter concrete wall with a washer and nut to resist pullout. The purlins and subpurlins are nailed to the plywood diaphragm to transfer the out-of-plane wall forces into the horizontal diaphragm system. The wall spans horizontally 8 feet between holdown devices resisting out-of-plane forces. The attachment provides resistance to

the inertial out-of-plane wall forces and provides restraint against P-Δ wall forces at the roof level.

The attachment may reach its limiting capacity in one of the following ways:

- Purlin to diaphragm nailing failure
- Holdown device bolt failure at purlin or subpurlin
- Holdown device yielding or fracture
- Bolt yielding in tension
- Bolt failure from concrete breakout

Using the example configuration, a capacity will be estimated for each of the mechanisms outlined above. The mechanism that has the lowest median capacity estimate will be used to develop a fragility function for the assembly.

Purlin to Diaphragm Nailing Failure. Diaphragm nailing consists of 10d nails at 6 inches on center over an 8-foot length of purlin or subpurlins. The capacity can be taken from AF&PA/ASCE 16-95, *Standard Load and Resistance Factor Design (LRFD) for Engineered Wood Construction*, (ASCE, 1996) Table C4.2.2.D as 260 pounds per nail. The total capacity is 8320 pounds.

Holdown Device Bolt Failure at Purlin or Subpurlin. The bolting consists of 2 5/8" Φ machine bolts through the 4×12 purlin or two 2×4 subpurlins, with 12 gage sideplates.

For the subpurlins (3 inches thick), *National Design Specification for Wood Construction* Table 11G yields a Z_{11} value of 2,270 lbs. For 2 bolts, the capacity is

$$C_{DB} = 4,540 \text{ lbs} \times \frac{2.16}{0.65} = 15,087 \text{ lbs} = \phi R_n$$

Holdown Device Yielding or Fracture. The Allowable Stress Design (ASD) capacity of the double holdown device is given in the manufacturer's catalog as $2 \times 1,956 = 3,913$ lbs. Converting to an LRFD design strength yields:

$$C_{Dd} = 3,913 \text{ lbs} \times \frac{2.16}{0.65} = 13,002 \text{ lbs} = \phi R_n$$

Bolt Yielding in Tension. ACI 318-05 Appendix D, provides the following tensile capacity:

$$C_{DAB} = (0.75)^2 (58)(.226)(2) = 14,747 \text{ lbs} = \phi R_n$$

Bolt Failure from Concrete Breakout. ACI 318-05 Appendix D provides the following design breakout strength:

$$N_{cb} = \frac{A_{NC}}{A_{NC0}} (\psi_{ec})_N (\psi_{ed})_N (\psi_c)_N (\psi_{cp}) N_b$$

where:

$$N_b = k_c \sqrt{f_c} (h_{ef})^{1.5}$$

$$N_b = 24 \sqrt{4,000} (4.25)^{1.5} = 13,299 \text{ lbs}$$

$$A_{NC} = (14.75)(20.5) = 302.4 \text{ in}^2$$

$$A_{NC0} = 9(4.25)^2 = 162.6 \text{ in}^2$$

$$(\psi_{ec})_N = 1.0 \text{ (no eccentricity)}$$

$$(\psi_{ed})_N = 1.0 \text{ (Camin} > 6.375)$$

$$(\psi_c)_N = 1.25 \text{ (cast-in-place)}$$

$$\psi_{cp} = 1.0$$

Substituting:

$$N_{cb} = \frac{302.4}{162.6} (1.0)(1.0)(1.25)(1.0)(13,299) = 30,916 \text{ lbs}$$

$$C_{DBr} = (0.70)(0.75)(30,916) = 16,231 \text{ lbs} = \phi R_n$$

Table 6-6 summarizes the design strengths and estimated median strength values, θ , for each of these limit states. For all failure modes, a C_q value of 1.0 and β value of 0.24 has been used.

Table 6-6 Limit State Strengths Out-Of-Plane Attachment

Limit State	ϕR_n (lbs)	Failure Category	θ (lbs)
Diaphragm nailing failure	8,320 lbs	Ductile	13,621
Holdown device bolt failure	15,087 lbs	Ductile	24,700
Holdown device yielding	13,002 lbs	Ductile	21,286
Bolt yielding in tension	14,747 lb	Ductile	24,143
Bolt failure at concrete breakout	16,231 lbs	Brittle	31,859

The lowest median capacity estimate is associated with diaphragm nailing. This estimate is significantly lower than that for other limit states, suggesting that it is the most likely to occur. The damage that can be anticipated from the occurrence of this damage state consists of splitting of the purlin and subpurlin and tear through of the nails through the diaphragm plywood. Replacement of the purlin and plywood and renailing are required to restore the original integrity.

Development of the fragility function for this limit state is as follows:

Step 1. Define this as a strength-limited damage state characterized by ductile performance.

Determine the median strength as:

$$\theta = C_q e^{(2.054 \beta_I)} \phi R_n$$

where $\phi R_n = 8,320$ lbs

$$\beta_I = \sqrt{\beta_D^2 + \beta_M^2 + \beta_C^2}$$

For the dispersions, assign

$$\beta_D = 0.10, \beta_M = 0.20, \beta_C = 0.10$$

$$\beta_I = \sqrt{(0.10)^2 + (0.20)^2 + (0.10)^2} = 0.24$$

$$C_q = 1.0$$

$$\text{Therefore, } \theta = (1.0)e^{(2.054)(0.24)}(8,320) = 13,621 \text{ lbs}$$

Step 2. Assign a dispersion

$$\beta = \sqrt{(\beta_I)^2 + 0.16}$$

$$\beta = \sqrt{(0.24)^2 + 0.16} = 0.54 \text{ or } \beta = 0.5$$

Table 6-7 summarizes the fragility function for out-of-plane wall-to-roof anchorage. Figure 6-15 plots this fragility function.

Table 6-7 Damage State Description for Wall Attachment (Purlin Nailing) – Out-of-Plane

Damage State	Damage Description	Repair Description	Median Strength (lbs)	Dispersion
DS1	Purlin/subpurlin splitting, nail tear out through ply, roofing tearing and distortion.	Shorings as needed, purlin, subpurlin replacement, plywood reinstallation and nailing, reroofing. Damage occurs over middle 1/3 of diaphragm span.	13,621	0.5

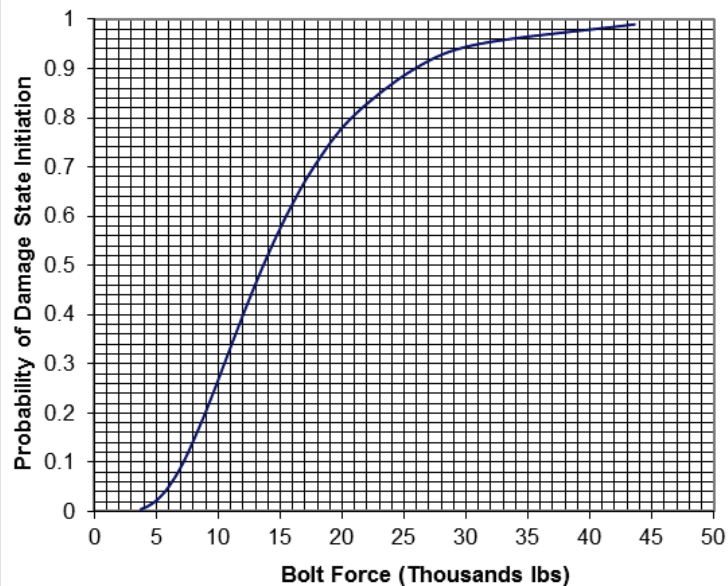


Figure 6-15 Fragility function for out-of-plane wall-to-roof nailing.

If the analytical model is configured as previously described, with wall panels modeled as beam elements with distributed mass spanning between the ground and roof, then the out-of-plane anchorage force demand can be directly determined from the analyses.

6.4 User-Defined Fragilities in PACT

User defined fragility specifications can be input into PACT using the **Fragility Specification Manager**. This utility is accessed via the **Control Panel**. Additional information regarding this utility can be found in Appendix C.

New fragility specifications are input by first entering a new fragility specification ID (Unifomat numbering used for components, see Chapter 2). This action will insert a blank specification form into the sequence displayed in the overview screen. Figure 6-16 illustrates the identification of a new fragility specification (C9994.002) into the library. Figure 6-17 illustrates the screen presented when the fragility specification is selected and the **Fragility Specification Details** tab at the top of the screen is clicked. The user can input the fragility specification **Name**, **Description**, and **Basic Units** of measure. The **Demand Parameter** can be drift, acceleration, or any user defined parameter, such as out-of-plane anchor force.

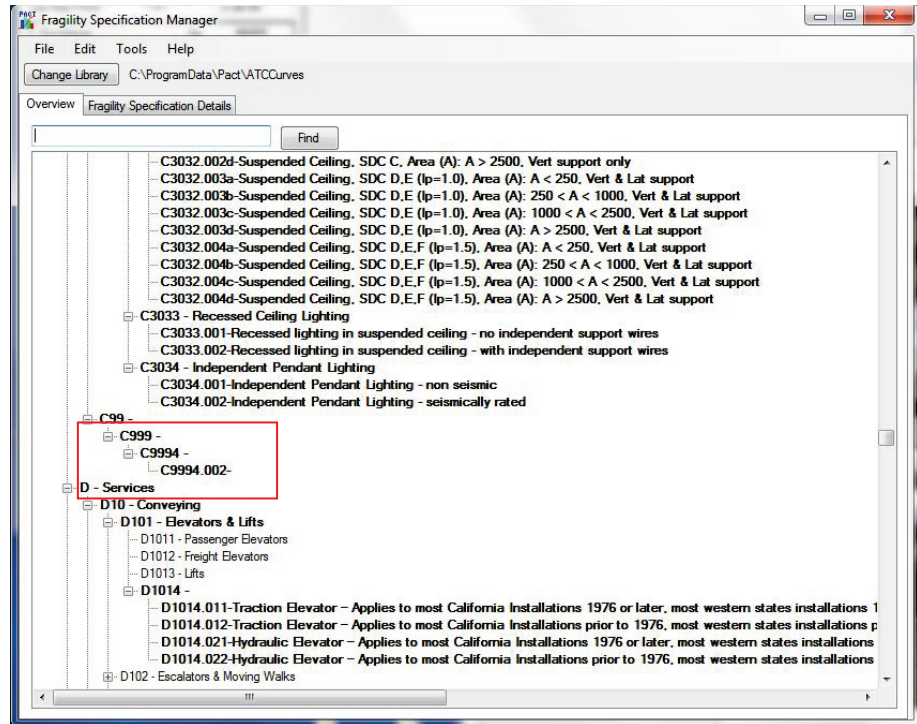


Figure 6-16 PACT Fragility Specification Manager showing new specification.

Figure 6-17 Fragility specification data input form.

Figure 6-18 shows the **Damage State** tab where new damage state data including median values and dispersions can be assigned. For each damage state, a consequence function must be entered. This is done via the **Add Consequence** tab at the left of the screen. For information on developing and inputting consequence function data, see Chapter 8. Multiple damage states can be inserted into the fragility specification by repeating the process.

The screenshot displays the 'Fragility Specification Manager' application window. The 'Overview' tab is selected, showing a tree view on the left with 'General Info' expanded, containing 'Damage State Type', 'Damage State 1', 'Add Consequence', 'Add Damage State Group', and 'Add Damage State'. The main area shows the 'Damage State' tab for 'C9994.002 *' of 763. The form includes fields for 'Name', 'Median (Ea):' (set to 0 with '(Unknown)' text), 'Dispersion:' (set to 0), and a 'Description:' text area. At the bottom right are 'Add Image' and 'Delete Image' buttons.

Figure 6-18 New fragility damage state definition form.

Nonstructural Fragility Calculation

7.1 Introduction

Volume 1, Section 3.8 presents procedures for calculation of fragility parameters for component damage states associated with limit states that can be predicted by calculation. This chapter illustrates those procedures for nonstructural components for damage states that can be predicted on the basis of the following calculated structural limit states:

- Strength-limited damage states when the occurrence of damage can be predicted by a demand exceeding a calculable force capacity
- Ductility-limited damage states when the occurrence of damage can be predicted by a demand exceeding a calculable amount of ductility
- Displacement-limited damage states when the occurrence of damage can be predicted by a displacement demand exceeding a calculable value
- Code-based limit states when damage can be predicted as a function of a code-specified demand parameter
- Overturning limit states when predicting overturning failure of unanchored components
- Sliding limit states when predicting sliding of unanchored components

Note that this methodology is generally not applicable to damage states associated with loss of electrical or mechanical function as these types of failures cannot typically be predicted by structural calculation. Shake table testing or earthquake experience data are generally necessary to develop fragility functions associated with loss of mechanical or electrical function, unless the loss of functions can be directly tied to a structural limit state.

7.2 Unanchored Components

Unanchored components are vulnerable to damage associated with overturning and sliding. Their vulnerability is dependent on the static coefficient of friction between the component and its resting surface, μ_s , listed in Table 7-1, the amount of distance the component can slide before experiencing damage, and the component's aspect ratio and weight

distribution. When sliding occurs, the amount of sliding displacement is controlled by the kinetic coefficient of friction. Volume 1, Section 3.8 presents a methodology for calculating fragility parameters for unanchored components based on predictive equations presented in ASCE/SEI 43-05, *Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities*, (ASCE, 2005b). This section illustrates the application of those procedures.

Table 7-1 Static Coefficient of Friction for Common Surface Combinations

Contact Surfaces	μ_s
Carpet-steel	0.45
Wood-steel	0.40
Poly/tetra/fluoro/ethylene - steel	0.27

The demand parameter used to determine the onset of overturning or sliding is peak total floor velocity, V_{PT} . V_{PT} is defined as the peak value of the vector sum of the ground velocity and the relative velocity between the floor and the ground.

7.2.1 Overturning

To illustrate the procedure, overturning fragility parameters for a fully loaded, 5-shelf metal bookcase is calculated. Figure 7-1 defines the basic geometric parameters including the tipping angle, α , the minimum horizontal projected distance from the center of gravity (cg) to the edge of the component's base, b , and the height of the component's center of gravity above the base, h .

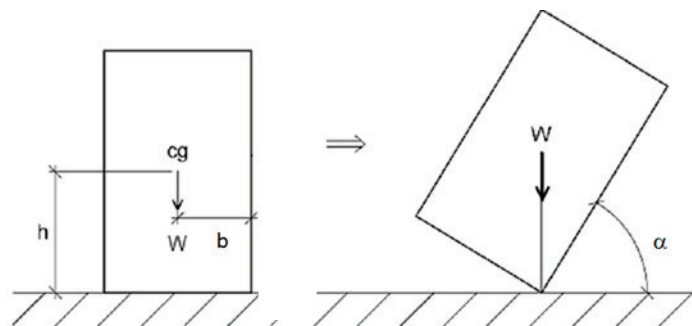


Figure 7-1 Overturning parameters for unanchored objects.

The goal of the procedure is to estimate the median peak total floor velocity at which overturning initiates and a dispersion to reflect the uncertainty.

The bookcase is 71 inches high and has a narrow dimension of 12-5/8 inches. It rests on hardwood floor. From Table 7-1, the static coefficient of friction between the bottom of the bookcase and the hardwood floor is 0.40.

$$h = 71/2 = 35.5 \text{ inches}$$

$$b = 12.625 / 2 = 6.31 \text{ inches}$$

The units for the calculation will be in inches, seconds and radians.

Step 1. Determine the critical tipping angle, α (in units of radians) at which the object is on the verge of overturning from Volume 1, Equation 3-5:

$$\alpha = \arctan\left(\frac{b}{h}\right)$$

$$b/h = 6.31/35.5 = 0.178$$

$$\alpha = \arctan(0.178) = 0.176 \text{ radians}$$

Step 2. Determine the horizontal spectral acceleration overturning capacity of the component, S_{aO} , in units of the acceleration due to gravity, g , from the critical tip angle α and the component's dimensions with Volume 1, Equation 3-6:

$$S_{aO} = \frac{2B}{\alpha}$$

where:

$$B = \cos(\alpha) + \frac{b}{h} \sin(\alpha) - 1 = \cos(0.176) + \frac{6.31}{35} \sin(0.176) - 1 = 0.016$$

$$S_{aO} = \frac{2B}{\alpha} = \frac{2(0.016)}{0.176} = 0.18 \text{ g}$$

Step 3. Comparison of the value of S_{aO} (0.18) with the static coefficient of friction (0.4) reveals that the object will likely overturn rather than slide.

Step 4. Determine rocking frequency, f_r , with Volume 1, Equation 3-10 and damping ratio, β_r , with Volume 1, Equation 3-11:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{2gB}{C_3 \alpha^2 h}}$$

$$\beta_r = \frac{\gamma}{\sqrt{4\pi^2 + \gamma^2}}$$

where:

C_3 is given by Volume 1, Equation 3-12:

$$C_3 = \frac{4}{3} \left(1 + \left(\frac{b}{h} \right)^2 \right) = \frac{4}{3} \left(1 + \left(\frac{6.31}{35.5} \right)^2 \right) = 1.38$$

γ is given by Volume 1, Equation 3-13:

$$\gamma = -2\ln(C_R)$$

C_R is given by Volume 1, Equation 3-14:

$$C_R = 1 - \frac{2(b/h)^2}{C_3} = 1 - \frac{2(.178)^2}{1.37} = 0.954$$

$$\gamma = -2\ln(0.954) = 0.0942$$

$$f_r = \frac{1}{2\pi} \sqrt{\frac{2gB}{C_3 \alpha^2 h}} = \frac{1}{2\pi} \sqrt{\frac{2(386)(0.016)}{1.38(0.176)^2(35.5)}} = 0.45 \text{ Hz}$$

$$\beta_r = \frac{\gamma}{\sqrt{4\pi^2 + \gamma^2}} = \frac{0.0942}{\sqrt{4\pi^2 + 0.0942^2}} = 0.015$$

Step 5. Determine the estimated median peak total floor velocity for overturning with Volume 1, Equation 3-8:

$$V_{PT} = \frac{S_{aOG}}{2\pi f_r D_{amp}}$$

where D_{amp} is given by Volume 1, Equation 3-9:

$$D_{amp} = 2.31 - 0.41 \ln(100\beta_r) = 2.31 - 0.41 \ln(1.5) = 2.14$$

$$\hat{V}_{PT} = \frac{S_{aOG}}{2\pi f_r D_{amp}} = \frac{0.178(386)}{2\pi(0.45)2.14} = 11.4 \text{ in / sec}$$

The median overturning value of V_{PT} is 11.4 inches/second. A dispersion of 0.50 is recommended to reflect the variability of the prediction. Figure 7-2 plots this fragility function.

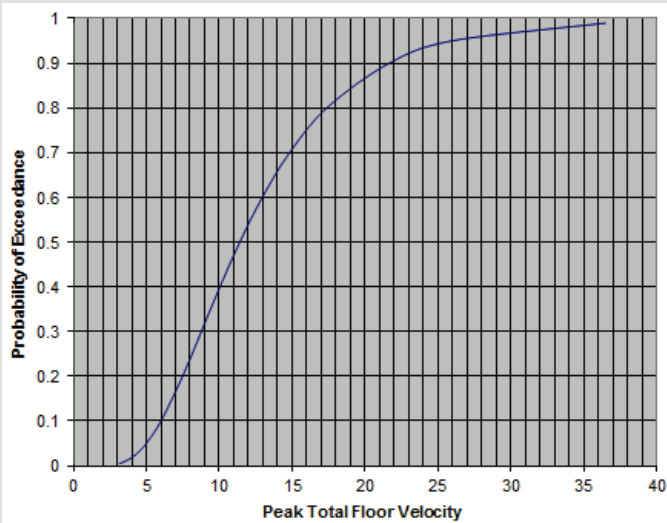


Figure 7-2 Fragility function for overturning of 5-shelf metal bookcase.

This procedure has been used to develop overturning fragility functions for a range of common unanchored office furniture. Table 7-2 and Table 7-3 present the calculated fragility values and provide some basic information used in the derivation of these parameters for metal bookcases and filing cabinets, respectively. Dispersion, β , is taken as 0.5 for both. The static coefficient of friction μ_s listed in these tables should be confirmed by the user.

Table 7-2 Calculated Fragility Values for Metal Bookcases

Number of Shelves	Depth (inches)	Height (inches)	μ_s	\hat{V}_{PT} (in/sec)
2	12.625	29	0.442	28.5
3	12.625	41	0.312	19.4
4	12.625	56	0.229	14.2
5	12.625	71	0.178	11.4
6	12.625	81.25	0.152	9.9

Table 7-3 Calculated Fragility Values for Filing Cabinets

Number of Drawers/Type	Narrow Plan Dim (inches)	Height (inches)	μ_s	\hat{V}_{PT} (in/sec)
2* Drawer/Vertical	15	24	0.64*	48.4
4 Drawer/Vertical	15	52	0.29	19.6
4 Drawer/Lateral	18.63	52.5	0.36	27.1
5 Drawer/Lateral	18.63	67.75	0.28	20.7

* Sliding likely to occur for common resting surfaces.

7.2.2 Sliding Displacement

Unanchored components mounted on surfaces with static coefficient of friction, μ_s , less than the horizontal overturning spectral acceleration capacity, S_{aO} , as defined in Section 7.2.1, will likely slide rather than overturn. Sliding components can be damaged by contact with other objects, can rupture attached utilities, and slide off mounting surfaces. Volume 1, Section 3.8 presents a methodology to determine the median peak floor velocity at which sliding displacements are expected to exceed a user-defined displacement, δ , at which damage is assumed to occur.

The methodology first determines whether the component will slide or overturn, as described in Steps 1 through 3 for overturning, above.

If it is determined that the component will slide, the median peak floor velocity, \hat{V}_{PT} , that causes sliding displacements in excess of the damage limit is calculated with Volume 1, Equation 3-15:

$$\hat{V}_{PT} = \frac{\sqrt{2\mu_D g \delta}}{1.37}$$

Table 7-4 provides mean estimates of μ_D , the dynamic coefficient of friction between the component and its supporting surface, for common contact surfaces.

Table 7-4 Dynamic Coefficient of Friction for Common Surface Combinations

Contact Surface	μ_D
Carpet - steel	0.40
Wood - steel	0.32
Poly/tetra/fluoro/ethylene - steel	0.20

The median peak total floor velocity value is determined for an unanchored component where μ_D , the assumed dynamic friction coefficient between the component's base and the bearing surface according to Table 7-4, is 0.40 and the tolerable sliding displacement, δ , is 2 inches. For this example, it is assumed that b/h for the component is such that the component slides, rather than rocks.

Substituting $g = 386.2 \text{ in/s}^2$,

$$\hat{V}_{PT} = \frac{\sqrt{(2)(0.4)(386)(2)}}{1.37} = 18.14 \text{ in/sec}$$

Under this methodology, a value of β of 0.5 is recommended. Figure 7-3 is a plot of the resulting fragility function.

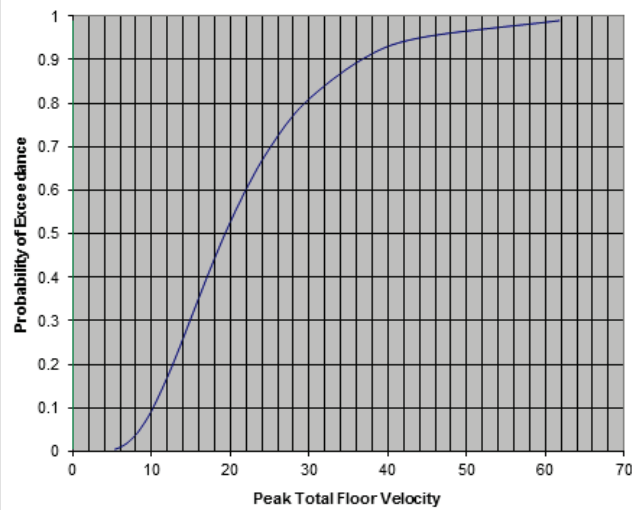


Figure 7-3 Fragility function for sliding of 5-shelf metal bookcase.

7.3 Anchored Components

In areas of high seismicity, nonstructural components are usually anchored. The seismic vulnerability of these components to earthquake ground motions is influenced by the capacity of the anchorage. The following sections present two alternative approaches for calculating anchorage fragility parameters for building components. The first of these approaches assumes that the component has been anchored in accordance with the building code provisions in effect at the time of installation. The second approach requires the user to have sufficient knowledge of the anchorage details to permit calculation of median demand values that correspond to anchorage failure modes.

Building component anchorage details are generally unique to each building, component type, and anchorage location within the building. Consequently, it is not possible to define generalized fragility parameters for nonstructural component anchorage.

7.3.1 Code-Based Limit State Determination of Anchorage Fragility

7.3.1.1 Recent Code Requirements

Seismic design of nonstructural component anchorage typically uses an equivalent static force method to determine required anchorage strength, typically identified by the parameter, F_p .

Prior to 1997

Prior to the 1997 edition, the Uniform Building Code (UBC) defined F_p by the equation:

$$F_p = Z I_p C_p W_p$$

where Z is a seismic zone factor reflecting the intensity of anticipated ground shaking, C_p is a nonstructural component coefficient, with a value assigned from a tabulation of different component types and corresponding values, I_p is a component importance factor usually assigned a value of 1.0 except for components in essential facilities, and W_p is the component weight. For critical components, the I_p factor could be assigned values of 1.25 or 1.5 depending on the code edition.

The component anchorage force, F_p , was used together with allowable stress design procedures that permitted a 1/3 increase on anchorage capacities. Nonstructural components located on the ground floor or in basement levels were permitted to be designed for 2/3 of the anchorage force obtained from the F_p equation. Anchorage of flexibly supported (i.e., vibration isolated) components typically required a twofold increase in the F_p force to account for dynamic amplification effects. For most nonstructural components (including non-vibration isolated mechanical and electrical equipment located above the first floor) in the highest seismic zone, the F_p coefficient had a value of 0.3 for equipment on elevated floors and 0.2 at the ground floor. Allowable stress loads can be converted to equivalent strength-level design forces by applying a factor of 1.4 to the allowable stress load.

1997 Uniform Building Code

The 1997 UBC, *Uniform Building Code* (ICC, 1997), adopted the following modified version of the F_p formula;

$$F_p = \frac{C_a I_p a_p}{R_p} [1 + 3 h_x / h_r] W_p$$

where C_a is a short period ground motion coefficient including soil condition effects, I_p the component importance factor similar to earlier codes, a_p is the component amplification factor, R_p in the force reduction factor, h_r is the structure's height above grade, and h_x is the height above grade at which the component is attached to the structure. According to 1997 UBC, the value of F_p cannot be taken less than $0.7 C_a I_p W_p$ and need not be taken greater than $4.0 C_a I_p W_p$.

In 1997 UBC, the value of C_a varies between 0 and 0.66 depending on the location of the site and the site soil conditions. For seismic zone 4 (not in the near field), the value of C_a is 0.44. Values of the term $[1 + 3 h_x/h_r]$ can range from 1 to 4. The value of the ratio of a_p / R_p for most listed items varies between 0.33 and 0.83. For mechanical and electrical equipment, the ratio of a_p / R_p is 0.33, except for unsnubbed vibration isolated equipment for which the ratio is 1.67. The potential range in anchorage design forces (in high seismic zones) is quite large, varying from as low as 0.3g to as high as 1.76g, depending on component type and location within the structure.

For rigidly mounted mechanical and electrical equipment located on soil sites in seismic zone 4, not in the near field and with $I_p = 1.0$, the value of F_p / W_p ranges from 0.308 at grade and lower floors to 0.58 at the roof level. Using the same seismic zone and I_p parameters, the value of F_p / W_p for vibration isolated equipment ranges from 0.73 at grade to 1.76 at the roof. When expansion anchors or shallow anchors (those with an embedment length to diameter ratio less than 8) are required, anchor strengths are double these values.

International Building Code and ASCE/SEI 7 after 2000

The 2000 through 2012 editions of the IBC, *International Building Code*, (ICC, 2000, 2009, 2012), as well as 2002 through 2010 editions of ASCE/SEI 7, *Minimum Design Loads for Buildings and Other Structures*, (ASCE, 2002, 2005a, 2010) specify the F_p coefficient using the following equation:

$$F_p = \frac{0.4 S_{DS} I_p a_p}{R_p} [1 + 2 z/h] W_p$$

where S_{DS} is a short period ground motion coefficient including site effects, z is the height above grade at the point of component attachment to the structure, h is the height of the structure above grade, and other parameters are as previously defined above. The value of F_p cannot be taken less than $0.3 S_{DS} I_p W_p$ and need not be taken greater than $1.6 S_{DS} I_p W_p$. Forces determined using this equation are considered to be strength level forces.

The value of S_{DS} varies between 0 and 2.5 depending on site location and class. The value of the $[1 + 2 z/h]$ term can vary from 1 to 3. The value of the ratio of a_p / R_p for most listed items varies between 0.29 and 1.0. For most rigidly mounted mechanical and electrical equipment, the a_p / R_p ratio ranges between values of 0.4 and 1.25. For vibration isolation mounted equipment, required anchor strength is increased by a factor of two, if the gap between the lateral restraint and equipment exceeds 1/4 inch. The potential range of

Second Edition Update

The discussion has been updated to consider ASCE/SEI 7-10 Supplement No. 1.

required anchorage strength (in high seismic zones) varies from as low as 30% to as high as 176% of equipment weight.

The nonstructural provisions of ASCE/SEI 7-10 were modified in Supplement No. 1 (ASCE, 2013) to include an overstrength factor applied to anchors in concrete and masonry where the force applied to the anchor is not limited by a ductile, yielding element. This provision is intended to prevent brittle failure of the anchors.

7.3.1.2 Procedure

Volume 1, Section 3.8 presents a code-based limit state procedure for the case where there is insufficient information available to directly calculate the anchorage capacity assuming that the original design met the requirements of the applicable building code.

Peak floor acceleration is the demand parameter used to evaluate anchorage failure. Most nonstructural components can be treated as rigid boxes, and therefore the equivalent static acceleration can be directly substituted for the peak floor acceleration. This is the demand parameter specified in the *Performance Assessment Calculation Tool* (PACT) provided in Volume 3 for anchored nonstructural components.

For vibration isolated equipment, peak floor acceleration can be amplified significantly. In anchorage design, this effect is accounted for by the specification of higher F_p forces for use in design. To reflect this demand amplification in the fragility calculation, it is recommended that the value of θ be divided by 2.5 for isolated components to convert from spectral acceleration to peak floor acceleration.

Where component anchorage was designed in accordance with a building code that specifies strength-level forces (1997 UBC, or 2000 or later edition of the IBC), the design resistance, ϕR_n , of an anchorage system, expressed as a peak floor acceleration, can be taken as the ratio F_p/W_p , where F_p and W_p are as described in the previous section. If anchorage was designed under codes that specified design forces in an allowable stress design format, the value of ϕR_n can be taken as $1.4 F_p/W_p$.

Prior to the adoption of ASCE/SEI 7-10 including Supplement No. 1, concrete anchorage was typically considered to have brittle failure modes associated with breakout type failures. The capacity of components designed after the adoption of Supplement No. 1 are more likely to be governed by the capacity of the component itself or its supports. In either case, the minimum median failure capacity of a nonstructural component designed to an

equivalent static acceleration coefficient F_p/W_p is given by Volume 1, Equation 3-2:

$$\theta = C_q e^{(2.81\beta)} \phi R_n$$

where:

$$C_q = 0.5$$

$$\beta = 0.5$$

θ = the median peak floor acceleration for anchorage failure

Yielding:

$$\theta = 2.04 \phi R_n$$

To obtain θ , the user must identify the building code under which component installation was designed and determine the equivalent static acceleration coefficient for the component and the anchorage. This will require knowledge of the building site (Z , C_a , S_{DS}), location within the building where the component is supported (h_x and h_r), and the appropriate I_p , a_p , and R_p coefficients.

The following examples illustrate application of this procedure, first for rigidly mounted equipment, next for isolation-mounted equipment, and lastly for out-of-plane anchorage for precast wall panel. The first two designs were done with allowable stress forces.

Rigidly mounted equipment is located in the building's basement (or first floor equipment room) in conformance with the 1994 UBC in Seismic Zone 4.

According to 1994 UBC:

$$Z = 1.0$$

$$I_p = 1.0$$

$$C_p = 0.3$$

Nonstructural components located in basement levels are permitted to be designed for 2/3 of the anchorage force:

$$F_p = 2 / 3 (1.0)(1)(0.3)W_p = 0.2W_p$$

$$\text{Thus } F_p / W_p = 0.2$$

Since the 1994 UBC specified design forces in allowable stress design format,

$$\phi R_n = (1.4) F_p / W_p = 1.4(0.2) = 0.28 \text{ g}$$

$$\theta = 2.04 \times 0.28 = 0.49 \text{ g and}$$

β is taken as 0.5.

Figure 7-4 plots this fragility function.

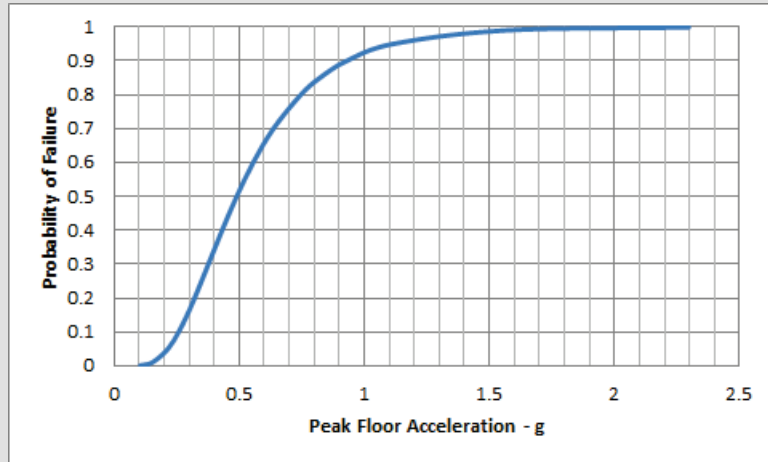


Figure 7-4 Fragility function for anchorage of rigidly mounted equipment designed under the 1994 UBC.

Vibration isolated equipment is located in the building's basement (or first floor equipment room) in conformance with the 1994 UBC in Seismic Zone 4.

$$Z = 1.0$$

$$I_p = 1.0$$

$$C_p = 0.3$$

Nonstructural components with vibration isolation require a twofold increase in the force to account for dynamic amplification:

$$F_p = (2)(1.0)(1.0)(0.3) = 0.6 W_p \text{ in allowable stress design format.}$$

$F_p / W_p = 0.6$ in allowable stress design format and thus, in strength format is given ϕR_n is given by:

$$\phi R_n = 1.4 \left(\frac{F_p}{W_p} \right) = 1.4(0.60 \text{ g}) = 0.84 \text{ g}$$

Note however, that because this equipment is flexibly mounted, the value of θ derived above should be divided by a factor of 2.5 to adjust for amplification of peak floor acceleration (to convert from spectral acceleration to acceleration). Thus:

$$\theta = (2.04)^{0.84/2.5} = 0.68 \text{ g}$$

Again, the dispersion is taken as $\beta = 0.5$. Figure 7-5 plots this fragility function.

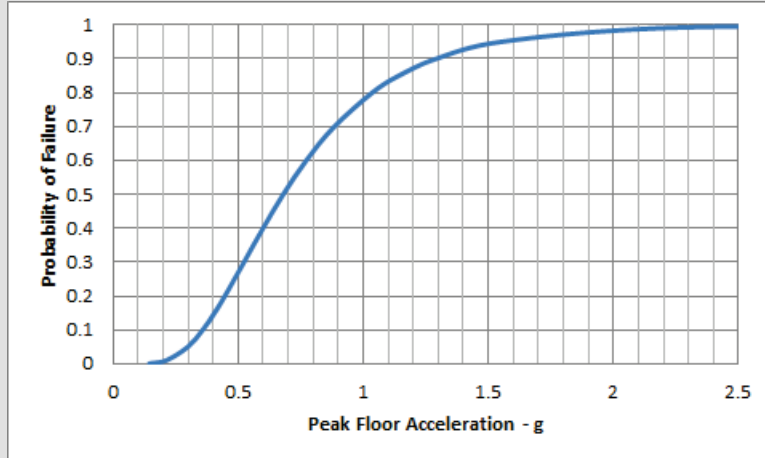


Figure 7-5 Fragility function for anchorage of vibration isolated equipment designed under the 1994 UBC.

A precast wall panel was designed and installed in conformance with ASCE/SEI 7-05. The wall panel is located between the roof and the floor just below. From ASCE/SEI 7-05:

$$S_{DS} = 1.0$$

$$I_p = 1.0$$

$$a_p = 1.0$$

$$R_p = 1.25$$

$$z/h = 1.0$$

$$F_p = \frac{0.4 \times 1.0 \times 1.0 \times 1.0 (1 + 2 \times 1.0) W_p}{1.25}$$

$$\frac{F_p}{W_p} = 0.96 < \frac{F_p}{W_p} \max = 1.6$$

Since ASCE/SEI 7-05 specifies design forces in a strength format, ϕR_n is equal to F_p/W_p .

$$\phi R_n = \frac{F_p}{W_p} = 0.96$$

$$\theta = 2.04(0.96) = 1.96 \text{ g}$$

The dispersion, β , is taken as 0.5.

7.3.2 ***Strength-Based Limit State Approach to Anchorage Fragility Calculation***

When details of a nonstructural component's anchorage design are known, the more detailed evaluation procedure of Volume 1, Section 3.8 can be used to calculate the fragility parameters. Note that with the introduction of the overstrength factor applied to anchors in concrete and masonry in ASCE/SEI 7-10 including Supplement No. 1, the strength capacity of the anchorage may no longer govern the lateral capacity of the nonstructural component.

The strength capacity of an anchorage embedded in concrete is typically determined using Appendix D of ACI 318-14, *Building Code Requirements for Structural Concrete and Commentary*, (ACI, 2014). This value can be adjusted using the procedures of Volume 1, Section 3.8 to obtain the median capacity associated with a failure mechanism (damage state). The median anchorage capacity can be expressed in terms of a floor acceleration, which serves as the fragility demand parameter.

This process requires the following steps:

Step 1. Determine the strength capacity of the anchorage detail for each failure mode using the procedure of Volume 1, Section 3.8 and ACI 318, Appendix D. Adjust the strength capacity to correspond to the median failure capacity.

Step 2. Determine the smallest median capacity of the anchorage using Volume 1, Section 3.8.

Step 3. Determine the forces on each individual anchorage for a given horizontal nonstructural component force, F_p , using the connection geometry.

Step 4. Solve for F_p that corresponds to the smallest anchorage median failure capacity.

Step 5. Divide F_p by the weight of the component, W_p , to determine the corresponding median floor acceleration. Assign a dispersion value according to Volume 1, Section 3.8.

The procedure is illustrated with an example below.

Assumptions:

- A rigidly mounted equipment item is supported on a foundation pad at the building's first floor level.
- The equipment is tall and penetrates the first floor, where it is attached for seismic and gravity forces.

- The equipment's center of gravity approximately aligns with the first floor slab, such that the anchor bolts at the first floor are in shear only.
- There are a total of 4 ¾-inch diameter, d_a , anchor bolts, using A36 threaded rod embedded 12 inches, l_e , into the slab with an 8 inch edge distance, c_{al} . Concrete strength is $f'_c = 3,000$ psi. The mounting pad has a depth of 24 inches. No supplementary reinforcing is present around the anchor bolts.
- The equipment weighs 50 kips.

Step 1. Determine the strength and median failure capacity of each anchor.

Based on calculations according to ACI 318-11, Appendix D, the anchorage capacity is found to be controlled by the yielding of the steel bolt in shear with:

$$\phi R_n = \phi A_{se,v} f_{uta} = 0.65(0.6) \frac{\pi}{4} \left(d_a - \frac{0.9743}{n_t} \right)^2 (58) = 7.6 \text{ kip}$$

Total dispersion is calculated using values given in Table 7-5 and Volume 1, Equation 3-3:

$$\beta = \sqrt{\beta_D^2 + \beta_M^2 + \beta_C^2}$$

Table 7-5 Dispersion Values for Failure Mode 1

Dispersion	Discussion	Value
Design (β_D)	Ductile behavior, well represented by design formula	0.05
Material (β_M)	A36 steel, from Volume 1, Table 3-4	0.15
Quality (β_C)	Low sensitivity to construction quality, from Volume 1, Table 3-5	0

$$\beta = \sqrt{(0.05)^2 + (0.15)^2 + (0)^2} = 0.16$$

Step 2. Determine the smallest median failure capacity of the anchorage.

Based on calculation, it is found that the failure modes of concrete breakout and concrete pryout have higher median strengths and thus are less likely to occur than the bolt shear mode.

Thus, the governing median failure (shear) capacity of an individual anchor is

$$\theta = C_q e^{(2.054\beta)} \phi R_n = (1.0) e^{0.328} 7.6 \text{ kip} = 10.6 \text{ kip}$$

Step 3. Determine the forces on an individual anchor. For the given component configuration, the anchorage on an individual anchor is $F_p / 4$.

Step 4. Solve for the F_p that results in an anchorage force equal to the median fragility anchorage failure force.

$$F_p / 4 = 10.6 \text{ kip}$$

$$F_p = 42.4 \text{ kip}$$

Step 5. Solve for the median failure acceleration

$$F_p / W_p = 42.4 / 50 = 0.85 \text{ g}$$

The dispersion, β , is taken as 0.30.

7.4 Displacement-Based Limit State Approach to Define Calculated Fragilities

Nonstructural components for which displacement based fragilities can be developed include exterior wall systems, such as precast cladding designed with slip joints of defined size and slide plate type seats for structural members crossing expansion joints.

Exterior wall systems are generally constructed with a gap to accommodate horizontal drift. Using geometric relationships, the size of the gap can be expressed as a story drift ratio that the wall panel system can accommodate before contact with adjacent panels occurs (usually at corners and column covers). Proprietary panel systems feature unique characteristics but suppliers can generally provide the drift or accommodation gap that inhibits adjacent panel contact.

The design story drift for the structure should be used for estimating the drift accommodation ratios of precast cladding systems. If this unknown, Table 7-6 provides guidance regarding the code minimum story drift ratio (often used by cladding system suppliers as the basis for the design) required by recent building codes as a function of the Occupancy Category referenced by the current code. Alternatively, the maximum story drift ratio for the building lateral system specified in the edition of ASCE/SEI 7 enforced at the time the structure was designed may be used.

Table 7-6 Suggested Drift Accommodation Ratios for Precast Cladding and Other Brittle Cladding Systems

Building Code	Building Occupancy Category According to ASCE/SEI 7)		
	II	III	IV
1994 UBC or earlier	0.012	0.012	0.012
1997 UBC	0.020	0.020	0.020
2000 IBC – 2009 IBC	0.020	0.015	0.010
2012 IBC	0.020	0.019	0.015

The drift ratio at which damage occurs can be taken as the drift accommodation ratio shown in the table plus an additional value (0.005 is recommended). Note that in some cases, cladding design can accommodate greater drift, either because of intentional design conservatism or because use of convenient dimensions, such as 1 inch gaps, resulted in more tolerance than required by the applicable code. If drawings depicting the gap system are available, users should determine if actual drift tolerance can be determined from these drawings. A dispersion of 0.5 is recommended for story drift related fragilities.

The example below illustrates the determination of the story drift fragility of a precast concrete exterior wall panel.

Assume a precast concrete exterior wall panel was installed in conformance with ASCE/SEI 7-05, $S_{DS} = 1.0$, $I_p = 1.0$.

From Table 7-6, the assumed accommodation drift ratio is 0.020

Therefore:

$$\theta = 0.020 + 0.005 = 0.25 \text{ with } \beta = 0.5.$$

Chapter 8

Consequence Function Development

8.1 Introduction

Consequence functions are used to convert component and building damage states into performance measures including repair costs, repair times, unsafe placarding probabilities, and casualties. As with each of the other performance assessment steps, uncertainties arise in the translation of damage states to consequences. Consequence functions reflect this uncertainty in the form of probability distributions of consequences for each damage state.

Volume 1, Section 3.9 provides guidelines for developing consequence functions. This chapter illustrates the consequence function development process and presents procedures that can be used to modify provided consequence functions to reflect the unique circumstances users may encounter in individual building assessments.

8.2 General Considerations

Repair cost and repair time consequence functions provided with the *Performance Assessment Calculation Tool* (PACT) provided in Volume 3 have been developed by professional cost estimators using component damage state repair descriptions for a reference location in the United States (Northern California) at a reference time (2011), neglecting uncertainty in contractor pricing strategies or construction cost escalation. Repair descriptions were developed in collaboration with engineering consultants familiar with repair techniques and cost estimators familiar with collateral cost and work. Repair cost and repair time estimates were developed to include all collateral work, such as finish removal and replacement, scaffolding, and debris removal, associated with each component damage state repair. Consideration is given to cost and time efficiencies that are gained by multiple component repairs occurring in a given realization. General contractor mark-up is included in the cost estimates. The repair time estimates do not include the time needed to design, permit, and fund the repair project, the time required to procure long lead time components that need replacement, or the time to mobilize the contractors and close the

Second Edition Update

The definition of repair time has been clarified.

project. The environmental impact estimates were generated directly from the repair cost estimates in collaboration between construction cost estimators and environmental life cycle assessment researchers.

For each damage state, a determination is made as to whether loss of life or serious injuries are possible as a result of the damage. For damage states deemed to present a potential for loss of life or serious injuries, an affected area is estimated. The affected area is that occupied floor space adjacent to the damaged component in which there would be risk of injury. The likelihood of loss of life or serious injuries in the impacted area is estimated based on the component's weight and location and judgment.

The likelihood of unsafe placard posting is determined using engineering judgment. For most nonstructural components, an unsafe placard posting is judged unlikely as a consequence of their damaged condition. A few notable exceptions include fire sprinklers (since their failure affects the post-earthquake fire life-safety of the building) and suspended ceiling systems (since their failure can create the impression of significant damage that may cause a post-earthquake inspector to post the building as unsafe). On the other hand, most structural components are judged to have the potential for triggering an unsafe placard posting since damage to these components can result in a reduction of the gravity or lateral-load carrying capacity of the building.

8.3 Calculation of Consequence Functions

8.3.1 Repair Cost

A detailed description of repair scope is needed to enable estimation of repair labor and materials. The repair description must include all work associated with repair of the actual damage as well as collateral work associated with removal and replacement of finishes, relocation of utilities, provision of scaffolding, and similar actions.

The following steps outline the process for converting a component damage state into a repair cost consequence.

8.3.1.1 Establish Required Repair Actions

Where multiple repair options exist, users must choose which strategy to use, or alternatively, select multiple strategies and develop consequences for each. In the latter case, the uncertainty of each method will be calculated by taking a weighted-average value of the costs associated with each as the median estimate of repair cost. Accordingly, in order to cover the range of potential repair options and cost, dispersions should be selected sufficiently large.

Typically, only one repair strategy will be selected, being the lowest-cost acceptable solution.

8.3.1.2 Establish Repair Boundaries and Interfaces

The repair scope should include all necessary access work, including removal and replacement of finishes, mechanical/electrical work or scaffolding. However, a considerable amount of overlap and double-counting of access work is possible in estimating repair work on a component basis. For example, repair of a structural element may require removal of mechanical/electrical system components that prevent access to the damaged structure. However, the mechanical/electrical systems may be directly damaged resulting in double-counting of the repair of these components.

For more severe damage states, it may be advisable to exclude removal and replacement of mechanical/electrical systems associated with a structural repair, assuming that as more severe damage occurs, these systems will become damaged and require repair by themselves. Users should consider the likelihood that these systems will be directly damaged and if so, exclude them from the user-defined consequence function being developed.

8.3.1.3 Consider Associated Work Items

The following items should generally be included in damage repair estimates:

- Temporary relocation and protection of building contents
- Removal and reinstallation of covering elements
- Cutting in, patching, and repairing of adjacent building elements
- Clean-up
- Staging and access
- Costs for these associated work items should include subcontractor level mark-up, including overhead and profit. General contractor mark-up should not be included since this is separately addressed.

8.3.1.4 Estimate the Repair Cost

Using an appropriate estimating methodology, develop an estimate for the repair cost. Since most repairs are not standard work found in cost estimating guides, it is usually necessary to formulate an estimate using local expertise and judgment regarding the labor hours and materials needed to execute the specific work required. Allowances should be included for scope not specifically identified.

8.3.1.5 Establish Repair Cost Ranges

PACT is structured to use probabilistically defined cost ranges. Input of values for the 10th, 50th, and 90th percentile repair costs capture this uncertainty. Median values and either the coefficient of variation (COV) or dispersion values calculated from the cost data, based on the selection of the distribution (normal or lognormal) are also input.

Best estimate, lower bound, and upper bound costs should be identified and then a lognormal or normal distribution should be fit to these bounds. The selection of the distribution is based on judgment.

In addition to identifying best estimate, lower, and upper bound estimates of repair costs, an adjustment based on economies of scale is also applied. Costs per unit of repair at lower bound quantities and upper bound quantities are indicated in the consequence function. For example, if fewer than three components are damaged in a realization, the unit repair cost has a median value of \$15,000 while if more than ten components require repair in a realization, the unit median cost decreases to \$8,000 per item. With this information, the user can enter a lower bound of three, with an associated median cost of \$15,000, and an upper bound of 10, with an associated median cost of \$8,000. For quantities intermediate to the upper and lower bounds, PACT applies linear interpolation.

8.3.1.6 Assign Dispersion

Dispersion values are based on the uncertainty in values of unit cost and are assumed to be constant regardless of the quantity of repairs that must be conducted.

8.3.2 Repair Time

Similar to estimating repair cost, a detailed description of repair scope is needed to enable estimation of repair time. The repair description must include all work associated with repair of the actual damage, as well as collateral work associated with removal and replacement of finishes, relocation of utilities, provision of scaffolding, and similar actions. The repair time estimates should not include the time needed to design, permit, and fund the repair project, long lead times, or the time to mobilize the contractors and close the project.

The following steps outline the process for converting the occurrence of a component damage state into a repair time consequence.

8.3.2.1 Establish Baseline Repair Time Estimate

The baseline repair time estimate is based on the total number of trade hours required to perform the work and can be generated directly from the total baseline repair cost or from the detailed line items of the cost estimate.

For repair work that is highly labor intensive, the most accurate approach is to estimate the labor hours for each detailed line item and sum them. This also provides a validation check on the cost estimate by ensuring that all complexity of labor has been considered.

A reasonable approximation can be obtained, however, by simply applying a labor factor to the overall baseline repair cost estimate, and dividing the result by an effective hourly rate for the likely labor mix. For example, if the baseline cost is \$10,000, and labor is assumed to make up 80% of the total cost, the labor cost is \$8,000. If the labor rate (fully burdened) is assumed to be \$80/hr, that represents 100 hours of work for repair.

8.3.2.2 Establish Repair Time Estimate Ranges

Variability in repair time estimates can be directly assigned as equal to the repair cost estimate variability. Users can also independently develop an estimate of variability using the detailed line item elements of the cost estimate and judgmental considerations on the difficulty of performing the work item. An important consideration with regard to repair time variability is that PACT computes the number of days of repair time by dividing the total labor hours determined for each realization by the number of workers that can be accommodated in the building during repair. This latter quantity justifies higher dispersions for repair time than are used for cost.

8.3.3 Unsafe Placards

Use of judgment is necessary to assess if the damage state is likely to result in unsafe placard posting. Consideration must be given to the appearance of damage, and the effect it may have on post-earthquake inspectors, as well as the actual effect the damage will have on the building's post-earthquake safety. Damage that significantly increases the probability of building collapse in aftershocks should trigger unsafe placarding, whether or not the damage is directly observable to post-earthquake inspectors. Similarly, damage that could appear substantive to post-earthquake inspectors should be assumed to be capable of triggering unsafe placarding, even though the actual reduction in building safety may be small.

The following steps outline the process for converting a component damage state into an unsafe placard consequence.

8.3.3.1 Determine Likelihood of Unsafe Placard

Unsafe placards are posted on buildings by inspectors performing rapid assessments of many buildings after an earthquake. These inspectors must apply individual judgment as to whether a building's safety has been impaired. These judgments are imperfect. If significant structural damage, such as shear failure of concrete columns is evident, inspectors are likely to post the building as unsafe. However, in many types of buildings, significant structural damage is not readily observable without removal of finishes. Therefore, when performing post-earthquake assessments, inspectors often rely on the extent of damage to nonstructural elements as an indicator of structural damage that is not itself readily visible. This methodology assigns an unsafe placard under two conditions:

- Actual damage sustained by the structure is such that a life-threatening condition actually exists either through impairment of required egress or fire protection systems, or through substantive reduction in structural resistance; or
- A preponderance of nonstructural damage such that there is the appearance that substantive structural damage has occurred whether or not this is actually the case.

For each damage state, users will need to assess whether an unsafe placard posting can occur as a consequence of the damage. For most nonstructural components, an unsafe placard posting is not likely to occur unless it affects the life safety function of the building or is present in such quantity that it can create a visual appearance that is suggestive of unobservable structural damage. For structural components, the more severe damage states are more likely to result in an unsafe placard posting since the resulting damage can affect the overall safety of the building.

8.3.3.2 Establish the Median Fraction of Total Quantity that will Trigger an Unsafe Placard

For each component damage state, a median fraction is estimated that reflects the number of damaged components out of the total number of similar components at a given story or floor that would result in an unsafe placard posting. Generally, the fraction of the total quantity that will result in unsafe placarding reduces with the severity of the damage state given that it takes fewer occurrences to affect either the actual or apparent effect on building safety. For example, special concentrically braced frames with wide flange braces are assigned the following fractions by damage state:

- DS1: Not applicable, unsafe placard posting not probable

- DS2: 60% of total quantity will result in unsafe placard posting
- DS3: 40% of total quantity will result in unsafe placard posting
- DS4: 20% of total quantity will result in unsafe placard posting

For the most severe structural component damage states, the percentage could be as low as 1%, when the damage state results in an obvious reduction in gravity load or seismic load carrying capacity.

8.3.3.3 Assign Dispersion

A dispersion value of 0.5 is recommended unless more detailed information is available.

8.3.4 Casualties

Judgment is required to assess if the damage state is likely to result in loss of life or serious injury. An impacted area and rate of severity must be defined for estimating casualty and serious injury.

The following steps outline the process for converting a component damage state into casualty consequences.

8.3.4.1 Determine Potential for Non-Collapse Casualties

For each damage state, the possibility of casualties considering the weight and location of the component should be determined. While the failure of most components will likely not result in loss of life, serious injury may still be possible.

8.3.4.2 Determine Affected Occupancy Areas

For those components with damage states identified to result in casualties, an affected area is estimated. The affected area is that occupied floor space adjacent to the damaged component in which there would be risk of injury or casualty. Population models are used to establish the number of persons likely to be present within the affected area.

For example, the occupied affected area for ceiling systems is estimated as the floor area directly underneath the ceiling. For HVAC ducting, the area is estimated as 15 square feet for ducts with less than 6 square feet of cross-sectional area, assuming a 5 feet length of 3 foot wide ducting falling to the floor below.

8.3.4.3 Determine Rate of Loss of Life in Affected Area

The likelihood of loss of life occurring from the component damage state is judged based on the component weight and location. For the vast majority of

components, such as HVAC ducting, the loss of life rate is taken as zero; however, other provided fragility specifications, such as “heavy” wall partitions and in-line fans, include non-zero values.

8.3.4.4 Determine Serious Injury Rate in Affected Area

Serious injury is defined as injury requiring hospitalization. Component damage states are more likely to result in serious injuries than loss of life. The serious injury rate represents the median percentage of people in the affected area that will be seriously injured. Generally, this percentage will be small since people have the opportunity to react to collapsing components and get out of the affected area and also because components may either fall towards or away from a person. Minor injuries, including scrapes, bruises, and even some lacerations not requiring hospitalization are not considered. For example, the serious injury rate is taken as 5% for HVAC ducting.

8.3.4.5 Assign Dispersion

A dispersion value of 0.5 should be used unless more detailed information is available.

8.3.5 Environmental Impact

Second Edition Update

Calculation of environmental impact estimates have been added.

The environmental impact estimates are directly derived from the construction cost estimate. Environmental impacts are estimated using the Economic Input-Output Life Cycle Assessment (EIO LCA) data (Carnegie Mellon University Green Design Institute, 2008) that correlate environmental impacts to the number of dollars spent in each industrial sector. The industrial sectors are defined by the North American Industry Classification System (NAICS). Examples of industrial sectors include ready-mix concrete manufacturing, adhesive manufacturing, and iron, steel pipe and tube manufacturing from purchased steel.

Two metrics are tracked in the environmental impact assessment: greenhouse gas emissions (measured in kg CO₂e) and energy consumption (measured in MJ). The scope of material impacts is limited to the ‘cradle-to-gate’ impacts of manufacturing, and does not include on-site construction impacts. Routine maintenance and disposal of materials at end-of-life are not considered. No environmental impact is assigned to labor, as is common in industry Life Cycle Assessments (LCA), and the impact of using temporary powered equipment is also excluded.

The following steps outline the process for converting a fragility repair cost consequence into environmental consequence.

8.3.5.1 Obtain the Repair Cost Estimate

See Section 8.3.1 for information about developing the repair cost estimate. The more detailed the cost estimate, the more detailed the LCA evaluation can be.

8.3.5.2 Allocate Costs to Industrial Sectors

The environmental impacts of the fragilities are based on the median value of the construction cost estimate. In the detailed cost estimate, the cost of each repair activity must be disaggregated and allocated into the following broad categories: labor, energy, rental equipment, and industrial sectors. The appropriate industrial sectors should be selected from the EIO LCA database for each work activity in the cost estimate. Finally, the cost in each applicable sector is summed. As previously stated, the scope of this study assumes zero environmental impact for labor, energy, and rental equipment, but allocating costs to these categories may assist in developing the overall allocations.

Cost allocation will require some judgement on how the costs should be distributed. In this assessment, the costs were allocated using professional judgement by a construction cost estimator.

8.3.5.3 Obtain Environmental Impact Factors

The EIO LCA database should be queried to obtain the environmental impact factors for the industrial sectors. Ensure that the 2002 Purchaser Price Model is selected when extracting the TRACI Impact Assessment and Energy factors. Before applying the environmental impact factors to the repair costs, the factors must be adjusted to reflect per dollar costs (\$1 instead of \$1 million) and inflation. The overall embodied environmental impacts can be calculated by multiplying environmental factors with the allocated repair costs determined in the previous step. These calculations can be consolidated by using matrix multiplication.

Regarding inflation: At the time of this writing, the reference year for the PACT data is 2011, while the reference year for the EIO-LCA data is 2002. The resulting inflation factor going from 2002 to 2011 was determined to be 1.45. Since the dollar units are in the denominator, the environmental impacts / \$ spent are divided by 1.45 to convert 2002 to values to 2011 values. From there, the same process can be repeated to convert 2011 values to present values.

8.3.5.4 Calculate Total Environmental Impacts

The total environmental impacts are calculated by multiplying the sector costs with the adjusted environmental impact factors. If per dollar values are desired, the total environmental impact can be divided by the total cost of the fragility or project. Multiplication by matrices is recommended for this step.

8.3.5.5 Assign Dispersion

A dispersion value of 0.5 is recommended unless more detailed information is available.

8.4 Example Application

This section illustrates the development of the consequence function for a low aspect ratio reinforced concrete shear wall of 8 inches or less thickness with a single curtain of reinforcement in damage state 2. The fragility and consequence functions for this component (B1044.001) are provided in the *Fragility Database* in Volume 3 which is referenced by PACT.

8.4.1 Estimation of Repair Cost

Damage state descriptions for this component were established through testing and include shear cracking, concrete spalling, jamb crushing, rebar buckling, and rebar fracture.

8.4.1.1 Establish the Required Repair Actions

Repair strategies are developed at a level of detail sufficient to approximate likely costs. Consideration is given to the length of cracks requiring epoxy grouting, extent of reinforcing requiring removal, and the process for splicing in place of new reinforcing with existing. For provided fragility groups, this information is accessible via the PACT **Fragility Specification Manager** utility under each damage state description.

The damage is not uniformly distributed across the wall. The majority of significant damage occurs at wall ends. The basis of measurement selected is a 25 foot long by 15 foot high wall section, judged to represent a reasonable panel size and story height. The area of this wall, 375 square feet, is used for repair cost estimations.

In addition to the unit of measure, it is necessary to identify the wall thickness and reinforcing steel density. If the consequence function is to include a range of these parameters, it may be necessary to include multiple fragility specifications and associated consequence functions to represent the different conditions.

8.4.1.2 Establish Repair Boundaries and Interfaces

In this example, the estimated repair costs do not include removal and replacement of any architectural finish.

8.4.1.3 Estimate the Repair Cost including Associated Work Items

Table 8-1 presents the median repair cost estimate for a B1044.001 wall in damage state 2.

Table 8-1 Repair Cost Estimate for Wall				
Wall repairs	Quantity	Unit	\$/ unit	Total (\$)
Grout injection at wall cracks (330 LF of crack per 100 SF of wall)	1,238	LF	8.00	9,904
Remove portion of concrete wall for access to reinforcing steel (15 SF per 100 SF of wall)	56	SF	75	4,200
Remove portion of buckled #8 reinforcing steel 12" long, replace reinforcing steel with mechanical splices each end (5 locations per 100 SF of wall)	19	EA	200.00	3,800
Install eight #4 ties at end of wall, re-bend horizontal reinforcing steel bars around new ties	2	EA	1,000.00	2,000
Cast 5000 PSI concrete at wall infill including formwork	56	SF	75.00	4,200

The information in Table 8-1 is extracted from in the *Consequence Estimation Tool – Structural* in Volume 3 in the **Standard Wall to 8"** tab.

In addition to the direct repair work, the repair work for a reinforced concrete shear wall may include the following elements:

- Office furniture relocation within the building and their protection
- Floor protection consisting of plywood and a membrane for a distance of 10' either side of the wall
- Rolling scaffold access to the work area
- Shoring of the structure as needed during the repair
- An allowance for removal and replacement of mechanical and electrical items such as power outlets, switches, and data outlets
- The cost of clean-up and removal of temporary protection

8.4.1.4 Establish Repair Cost Ranges

Repair cost ranges are established for repair items based on a three point estimating approach, using high, low, and best estimate values. For example, furniture relocation is estimated at \$1,000 for the best estimate value, with a

range from \$500 to \$3,000. Installation of reinforcing at the ends of a wall is estimated at \$2,000 for the median value, with a range from \$0, representing no boundary damage, to \$4,000, representing extensive boundary damage.

The dispersion, β , value is set based on review of the resulting three point estimate. For user-generated fragility specifications, it is possible to use an overall β estimate, without first calculating the three point estimate, depending on user comfort with range estimates.

In this example, baseline estimate pricing and efficiencies assumed four to ten walls being repaired. Fewer than eight walls would result in lower efficiency and increased waste due to short orders. More than twenty six walls would lead to increases in efficiency of operations. The costs for wall counts below four increase by 20%, and the costs for walls counts above twenty six are decreased by 20%.

8.4.2 Estimation of Repair Time

For the above example, labor hours are estimated by line item, resulting in a median estimate of 15.8 days for the repair.

8.4.3 Estimation of Environmental Impacts

In this example, global warming potential and embodied energy are estimated by breaking down the repair cost estimate and multiplying the costs with environmental impact factors from the United States Environmentally Extended Input-Output (USEEIO) database (available at: <https://catalog.data.gov/dataset/useeio-v1-1-matrices>, last accessed September 28, 2018).

8.4.3.1 Obtain the Repair Cost Estimate

Refer to Table 8-1 for the median repair cost estimate for a B1044.001 wall in damage state 2.

8.4.3.2 Allocate Costs to Industrial Sectors

The industrial sectors were selected from the USEEIO database. The percentage cost allocations of the work activities are shown in Table 8-2. The result total cost allocations are shown in Table 8-3.

8.4.3.3 Obtain Environmental Impact Factors

The environmental impact factors extracted from the USEEIO database for the industrial sectors in this example are shown in Table 8-4. Note that in the database, global warming potential is labeled “impact potential/gcc/kg co2 eq” and energy is labeled “resource use/enrg/mj.”

Table 8-2 Percentage Cost Allocations for Wall

Work Activity		% Labor	% Energy	% Rental Tools/ No impact	Industrial Sectors						
					% Adhesive	% Cleaning	% Concrete	% Electrical	% Plastic film	% Plywood	% Steel – Fabricated
Remove, store and reinstall office furniture and equipment		94	1	0	0	5	0	0	0	0	0
Temporary	Floor protection	94	1	0	0	0	0	0	5	0	0
	Scaffolding or work platform	74	1	25	0	0	0	0	0	0	0
Wall repair	Grout injection at wall cracks...	59	1	0	40	0	0	0	0	0	0
	Remove portion of concrete...	79	1	10	0	10	0	0	0	0	0
	Remove portion of buckled #8...	59	1	0	0	0	0	0	0	0	40
	Install eight #4 ties...	59	1	0	5	0	0	0	0	0	35
	Cast 5000 PSI concrete...	49	1	10	0	0	35	0	0	5	0
Mechanical and electrical modifications or as required for repair work		74	1	0	0	0	0	25	0	0	0

Table 8-3 Resulting Total Cost Allocations for Wall

Total Cost (\$)	Labor (\$)	Energy (\$)	Rental Tools/ No Impact (\$)	Industrial Sectors						
				Adhesive (\$)	Cleaning (\$)	Concrete (\$)	Electrical (\$)	Plastic film (\$)	Plywood (\$)	Steel – Fabricated (\$)
31854	20876	319	1403	4062	470	1470	750	75	210	2220

Table 8-4 Environmental Impact Factors from USEEIO Database for Select Industrial Sectors

Industrial Sector	Global Warming Potential (kg CO ₂ e / \$)	Embodied Energy (MJ / \$)
Adhesive	0.89	21.09
Cleaning	0.17	4.94
Concrete	2.24	16.55
Electrical	0.25	4.73
Plastic film	0.74	18.59
Plywood	0.59	12.19
Steel - fabricated	0.85	26.02

The factors were then adjusted for inflation, converting from 2013 (USEEIO reference year) to 2011 (PACT reference year), by dividing by the ratio of gross domestic product in the construction sector in 2013 to 2011 from U.S. Bureau of Economic Analysis (available at <https://www.bea.gov/>, last accessed September 28, 2018). The inflation-adjusted gross outputs for the construction sector were 1139.7 in year 2013 and 1008.60 in year 2011, and thus the inflation or “deflation” factor going from year 2013 to 2011 was calculated as $1008.60/1139.7 = 0.88$. The inflation-adjusted environmental impacts are shown in Table 8-5. Also, ‘global warming potential’ was renamed to ‘embodied carbon.’

Table 8-5 Adjusted Environmental Impact Factors

Industrial Sector	Embodied Carbon (kg CO ₂ e/\$)	Embodied Energy (MJ/\$)
Adhesive	1.01	23.84
Cleaning	0.19	5.58
Concrete	2.54	18.70
Electrical	0.28	5.35
Plastic film	0.84	21.00
Plywood	0.66	13.77
Steel - fabricated	0.96	29.40

8.4.3.4 Calculate Total Environmental Impacts

The calculation for total environmental impact are shown below using matrix multiplication. Essentially, Table 8-3 is multiplied with Table 8-5.

$$\begin{aligned}
 & [\text{Sector costs}] \times [\text{environmental impact factors} / \$ \text{ in sector}] = [\text{overall environmental impacts}] \\
 & = [20,876 \quad 319 \quad 1,403 \quad 4,062 \quad 470 \quad 1,470 \quad 750 \quad 75 \quad 210 \quad 2,220] \\
 & \quad \times \begin{bmatrix} 1.01 & 23.84 \\ 0.19 & 5.58 \\ 2.54 & 18.70 \\ 0.28 & 5.35 \\ 0.84 & 21.00 \\ 0.66 & 13.77 \\ 0.96 & 29.40 \end{bmatrix} \\
 & = [9,785 \quad 178,184]
 \end{aligned}$$

Thus, the total environmental impacts for this fragility, an 8” thick standard concrete wall with dimensions of 25’ × 15’ in DS2 are:

Embodied carbon = 9,785 kg CO₂e

Embodied energy = 178,184 MJ.

8.5 Consequence Functions in PACT

8.5.1 Provided Consequence Functions in PACT

Consequence functions have been developed for fragility groups that are provided in the *Fragility Database* which is referenced by PACT. The **Cost Summary** tab of the *Fragility Database* contains the data developed in both of the *Consequence Estimation Tools*. In addition to the calculated low (10th percentile, P10), best estimate (50th percentile, P50), and high (90th percentile, P90) values of repair cost and repair time, the **Cost Summary** tab also includes information regarding the expected distribution of the consequence functions (normal or lognormal), relevant COV and dispersion values, as well as the lower and upper quantity values. Note that the *Fragility Database* provides the repair cost and repair time information per fragility unit of measure. Thus, best estimate repair cost of a reinforced concrete shear wall (B1044.001) is displayed as \$36 × 144 square feet = \$5,180 in the *Fragility Database* and PACT. All of the above information is also presented in the *Fragility Specification*.

8.5.2 User-Defined Consequence Functions

User-defined consequence functions are input, or existing ones are modified using the PACT **Fragility Specification Manager** utility. This utility can be accessed via the PACT **Control Panel**. The following sections describe the steps for adding new or modifying existing fragility specifications.

Consequence functions should be provided for each fragility specification included in the fragility database. For example, to add a new, low aspect ratio concrete shear wall fragility specification, the + button on the **Fragility Specification Details** tab of the **Fragility Specification Manager** is selected, as shown in Figure 8-1:

This will bring up the **Add New Fragility** window as shown in Figure 8-2. An appropriate fragility specification number per the modified NISTR system is entered and clicking **OK** to bring up additional windows for entry of data. The resulting, blank fragility specification is ready to be completed with the associated fragility and consequence function information.

Repair cost consequence information is input at the **Consequence Functions** tab as indicated in Figure 8-3. The unit of measure is dollars.

Repair cost consequence information is requested for both the lower quantity and upper quantity values to incorporate economies of scale. The resulting repair cost curve is automatically generated as shown in Figure 8-3. Figure 8-3 illustrates an example, where the repair cost for less than 5 units is \$5,000 and \$3,000 for more than 15 units.

Users must indicate the **Curve Type** (either normal or lognormal) in the dropdown menu in Figure 8-3. In this example, the repair cost curve assigned is “normal” and the associated coefficient of variation (COV) is input into the cell. If the repair cost curve is lognormal, the associated dispersion (standard deviation of the logs of the values or β) value will be requested.

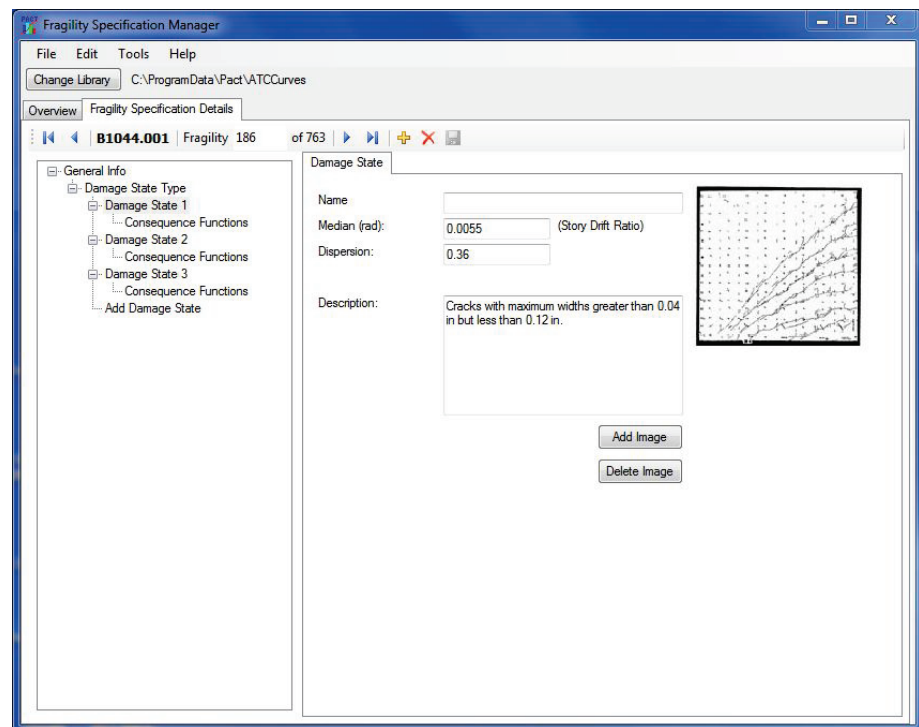


Figure 8-1 Initiating a new fragility specification in Fragility Specification Manager.

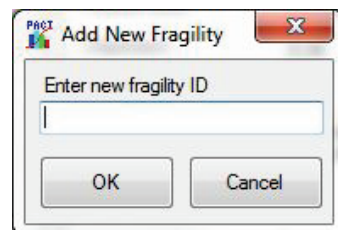


Figure 8-2 Add New Fragility window.

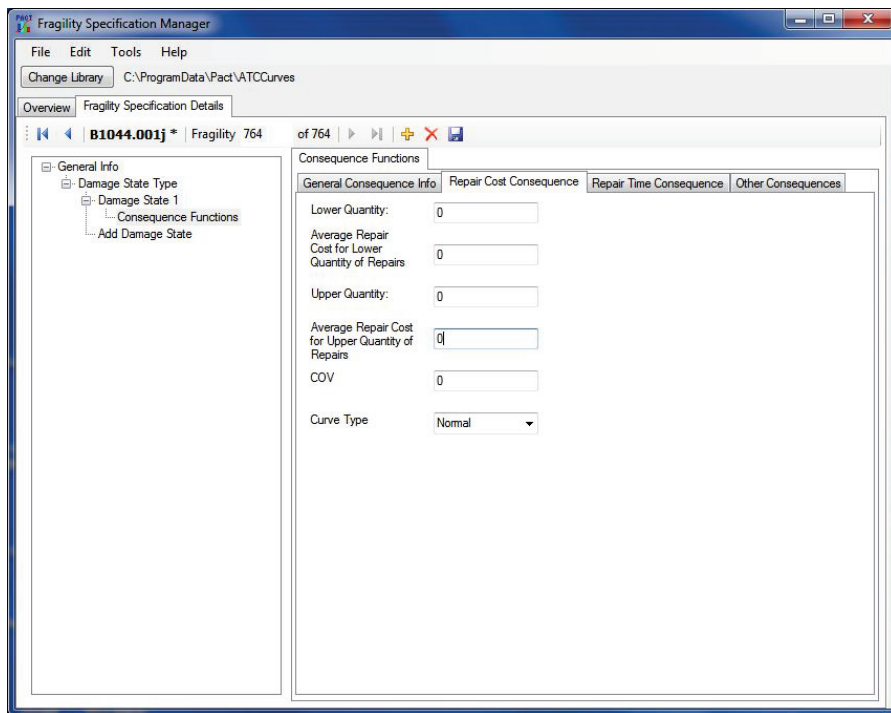


Figure 8-3 Consequence Function input window.

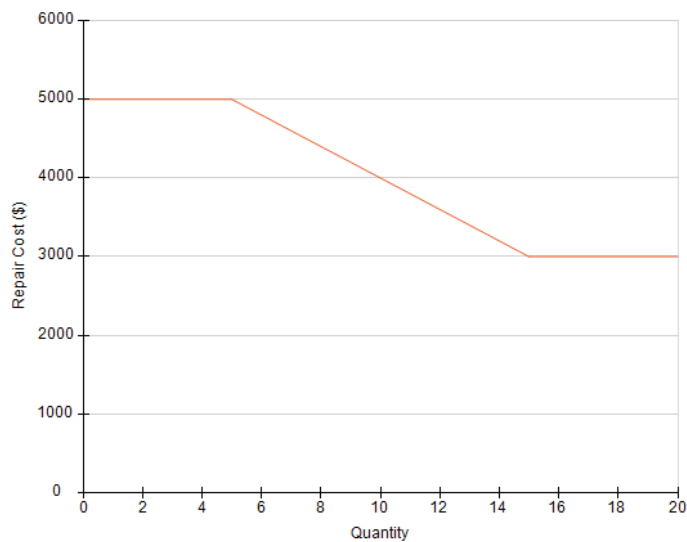


Figure 8-4 PACT graph showing upper and lower bound repair cost data.

Repair time consequence information is input in a similar manner to repair costs. The unit of measure is days. The economy of scale treatment is similar for both lower and upper quantities.

If a component damage state is likely to result in an unsafe placard posting, the box **Possible Unsafe Placard Consequences**, shown in Figure 8-5 in the **Other Consequences** tab, is checked.

The associated median fraction and dispersion values are input in the two boxes below the flag.

When it is judged likely that the damage state will result in either fatality or serious injury, the **Potential for Non-Collapse Casualties** box should be checked, as shown in Figure 8-6.

Information regarding **Occupied Area Affected Per Performance Group Unit**, along with the median and dispersion values can be input here.

If the repair time of a component is expected to be affected by long lead times for procurement, such as HVAC equipment and elevators, then the **Use Long Lead Time Flag** box should be checked. Note that the actual lead time is not included in the repair time estimate.

The **Environmental Losses** produced by PACT are also shown in this tab. If needed, the values for environmental impacts can be changed here.

Consequence Functions

General Consequence Info | Repair Cost Consequence | Repair Time Consequence | Other Consequences

Unsafe Placard Consequences

Possible Unsafe Placard Consequences: ☐

Fraction of Total Quantities to Trigger Unsafe Placard

Median: This fraction should relate to the total quantity from all Performance group in this damage state using this fragility

Dispersion:

Non-Collapse Casualties

Potential for Non-Collapse Casualties: ☐ Fatality Rate in Affected Area: Median: Dispersion:

Occupied Area Affected Per Performance Group Unit (sq. ft.): Injury Rate in Affected Area: Median: Dispersion:

Long Lead Time

Use Long Lead Time Flag ☐

Environmental Losses

Embodied Energy Median (MJ): Dispersion: Curve Type:

Carbon Emissions Median (kg): Dispersion: Curve Type:

Figure 8-5 Other Consequences tab, Unsafe Placards input.

Consequence Functions

General Consequence Info Repair Cost Consequence Repair Time Consequence Other Consequences

Unsafe Placard Consequences

Possible Unsafe Placard Consequences: ☐

Fraction of Total Quantities to Trigger Unsafe Placard

Median: This fraction should relate to the total quantity from all Performance group in this damage state using this fragility

Dispersion:

Non-Collapse Casualties

Potential for Non-Collapse Casualties: ☒ Fatality Rate in Affected Area: Median: Dispersion:

Occupied Area Affected Per Performance Group Unit (sq. ft.): Injury Rate in Affected Area: Median: Dispersion:

Long Lead Time

Use Long Lead Time Flag ☐

Environmental Losses

Embodied Energy Median (MJ): Dispersion: Curve Type:

Carbon Emissions Median (kg): Dispersion: Curve Type:

Figure 8-6 Other Consequences tab, Casualty input.

8.5.3 Other Considerations

User-defined consequence functions are not adjusted by time or location factors built into PACT. Thus, if the user-defined function is to be used at a later time or a different location, it must be adjusted by the user to reflect these changes.

Appendix A

Structural Component Fragility Specifications

Table A-1 Structural Steel Elements (B103)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/ Comments/ Notes	Fragility Classification Number
Miscellaneous Structural Steel Components/ Connections	Gravity beam connection	Bolted shear tab	-	B1031.001
	Column base plate	-	-	B1031.011a, B1031.011b, B1031.011c
	Column splice	Welded	-	B1031.021a, B1031.021b, B1031.021c
Structural Steel Braced Frame	Special Concentrically Braced Frame (CBF): balanced design criteria, Tapered gussets, AISC minimum standard	Wide flange braces (balanced design)	Chevron brace	B1033.001a, B1033.001b, B1033.001c
			Single diagonal brace	B1033.002a, B1033.002b, B1033.002c
			X brace	B1033.003a, B1033.003b, B1033.003c
		Hollow structural section (HSS) braces (balanced design)	Chevron brace	B1033.011a, B1033.011b, B1033.011c
			Single diagonal brace	B1033.012a, B1033.012b, B1033.012c
			X brace	B1033.013a, B1033.013b, B1033.013c
		Hollow structural section (HSS) braces (tapered gussets)	Chevron brace	B1033.021a, B1033.021b, B1033.021c
			Single diagonal brace	B1033.022a, B1033.022b, B1033.022c
			X brace	B1033.023a, B1033.022b, B1033.023c
		Hollow structural section (HSS) (AISC minimum standard)	Chevron brace	B1033.031a, B1033.031b, B1033.031c
			Single diagonal brace	B1033.032a, B1033.032b, B1033.032c
			X brace	B1033.033a, B1033.032b, B1033.033c
		Double angle braces (AISC minimum standard)	Chevron brace	B1033.041a, B1033.041b, B1033.041c
			Single diagonal brace	B1033.042a, B1033.042b, B1033.042c
			X brace	B1033.043a, B1033.043b, B1033.043c

Table A-1 Structural Steel Elements (B103) (continued)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/ Comments/ Notes	Fragility Classification Number
Structural Steel Braced Frame (continued)	Ordinary Concentrically Braced Frame	Compact brace shape (wide flange, HSS, double angles)	Chevron brace	B1033.051a, B1033.051b, B1033.051c
			Single diagonal brace	B1033.052a, B1033.052b, B1033.052c
			X brace	B1033.052a, B1033.053b, B1033.053c
		Brace at ductile slenderness limit (wide flange, HSS, angle)	Chevron brace	B1033.061a, B1033.061b, B1033.061c
			Single diagonal brace	B1033.062a, B1033.062b, B1033.062c
			X brace	B1033.063a, B1033.063b, B1033.063c
		Basic design for factored loads only (wide flange, HSS, angle)	Chevron brace	B1033.071a, B1033.071b, B1033.071c
			Single diagonal brace	B1033.072a, B1033.072b, B1033.072c
			X brace	B1033.073a, B1033.073b, B1033.073c
	Buckling-Restrained Brace (BRB) Frame	-	Chevron brace	B1033.101a, B1033.101b, B1033.101c
		-	Single diagonal brace	B1033.111a, B1033.111b, B1033.111c
	Eccentrically Braced Frame (EBF)	Shear link	No floor beams	B1035.061a, B1035.061b
			With floor beams	B1035.062a, B1035.062b
Structural Steel Moment Frame	Post-Northridge Reduced Beam Section (RBS)	Welded Web	-	B1035.001, B1035.002, B1035.011, B1035.012
	Post-Northridge not RBS	-	-	B1035.021, B1035.022, B1035.031, B1035.032
	Pre-Northridge	Welded Unreinforced Flange-Bolted WUF-B	-	B1035.041, B1035.042, B1035.051, B1035.052

Table A-2 Reinforced Concrete Elements (B104)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/ Notes	Fragility Classification Number
Reinforced Concrete Moment Frame	ACI 318 Special Moment Frame (SMF)	Beam yield	-	B1041.001a, B1041.001b, B1041.002a, B1041.002b, B1041.003a, B1041.003b
		Weak joints	$\Sigma M_c / \Sigma M_b > 1.2$ $P_u(col) < 0.6 f_c' A_g$ Joint $V/V_n < 1.2$ Compliant transverse reinforcement	B1041.011a, B1041.011b, B1041.012a, B1041.012b, B1041.013a, B1041.013b
	ACI 318 Intermediate Moment Frame (IMF)	Beam or column shear response	Joint shear damage	B1041.021a, B1041.021b, B1041.022a, B1041.022b, B1041.023a, B1041.023b
	ACI 318 Ordinary Moment Frame (OMF)	Beam yield, weak joints	Joint shear damage $\Sigma M_c / \Sigma M_b > 1.2$ $P_u(col) < 0.6 f_c' A_g$	B1041.031a, B1041.031b, B1041.032a, B1041.032b, B1041.033a, B1041.033b
		Column yield Joint shear yield	$\Sigma M_c / \Sigma M_b < 0.8$ Beam, Col: $V_n > V_e$	B1041.041a, B1041.041b, B1041.042a, B1041.042b, B1041.043a, B1041.043b
		Beam yield (flexure or shear) Weak joints	Beam: $V_n < V_e$	B1041.051a, B1041.051b, B1041.052a, B1041.052b, B1041.053a, B1041.053b
		Column yield (strong joints)	$P_u(col) < 0.6 f_c' A_g$ Column: $V_n < V_e$	B1041.061a, B1041.061b, B1041.062a, B1041.062b, B1041.063a, B1041.063b
		Weak columns with high axial load (strong joints)	$P_u(col) > 0.6 f_c' A_g$ Column: $V_n < V_e$	B1041.071a, B1041.071b, B1041.072a, B1041.072b, B1041.073a, B1041.073b
	ACI 318 Non-Conforming Moment Frames	Weak joints, beam yield	$\Sigma M_c / \Sigma M_b > 1.2$ $V/V_n > 1.2$ Or Non-compliant Transverse Beam Reinforcement	B1041.081a, B1041.081b, B1041.082a, B1041.082b, B1041.083a, B1041.083b
		Weak joints, column yield	$\Sigma M_c / \Sigma M_b < 0.8$ $(V_p/V_n)_{col} < 0.6$ Joint $V/V_n > 1.2$ Or Transverse Column Reinforcement with 90° hooks	B1041.091a, B1041.091b, B1041.092a, B1041.092b, B1041.093a, B1041.093b

Table A-2 Reinforced Concrete Elements (B104) (continued)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/Notes	Fragility Classification Number
Reinforced Concrete Moment Frame (continued)	ACI 318 Non-Conforming Moment Frames (continued)	Weak beams, strong joints (beam flexure or shear)	Beam with High $V/b_w d(f_c')^{1/2}$ Or Non Compliant Transverse Beam Reinforcement	B1041.101a, B1041.101b, B1041.102a, B1041.102b, B1041.103a, B1041.103b
		Weak columns (flexure or shear yield) Low to moderate axial column loads	$\Sigma M_c / \Sigma M_b < 0.8$ $(V_p / V_n)_{col} > 1.0$ $P_u(col) > 0.6 f_c' A_g$	B1041.111a, B1041.111b, B1041.112a, B1041.112b, B1041.113a, B1041.113b
		Weak columns strong joints, high axial	$\Sigma M_c / \Sigma M_b < 0.8$ Col $V_n < V_\ell$ $P_u(col) > 0.6 f_c' A_g$	B1041.121a, B1041.121b, B1041.122a, B1041.122b, B1041.123a, B1041.123b
		Inadequate reinforcement development (beam or column)	Inadequate Anchorage, Splices, Discontinuous Reinforcement	B1041.131a, B1041.131b, B1041.132a, B1041.132b, B1041.133a, B1041.133b
Reinforced Concrete Shear Wall	Concrete link beam	Diagonally reinforced	Aspect ratio between 1.0 and 2.0	B1042.001a, B1042.011a, B1042.021a
			Aspect ratio between 2.0 and 4.0	B1042.001b, B1042.011b, B1042.021b
		Conventionally reinforced	Aspect ratio between 1.0 and 2.0	B1042.002a, B1042.012a, B1042.022a
			Aspect ratio between 2.0 and 4.0	B1042.002b, B1042.012b, B1042.022b
	Rectangular low aspect ratio wall $h/l < 1.0$	8 inches or less thick	Planar, single curtain reinforcement	B1044.001, B1044.002, B1044.003
		8"-24" thick	Planar, double curtain reinforcement	B1044.011, B1044.021, B1044.012, B1044.022, B1044.013, B1044.023
	Low-rise wall	8 inches or less thick	Return flanges, single curtain reinforcement	B1044.031, B1044.032, B1044.033
		8"-24" thick	Return flanges, double curtain reinforcement	B1044.041, B1044.051, B1044.042, B1044.052, B1044.043, B1044.053
		8 inches or less thick	Boundary columns, single curtain reinforcement	B1044.061, B1044.062, B1044.063

Table A-2 Reinforced Concrete Elements (B104) (continued)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/Notes	Fragility Classification Number
Reinforced Concrete Shear Wall (continued)	Low-rise wall (continued)	8"-24" thick	Boundary columns, double curtain reinforcement	B1044.071, B1044.081, B1044.072, B1044.082, B1044.073, B1044.083
	Slender wall $h/l > 2.0$	12 inches thick	15 feet long	B1044.091
			20 feet long	B1044.092
			30 feet long	B1044.093
		18 inches thick	15 feet long	B1044.101
			20 feet long	B1044.102
			30 feet long	B1044.103
		30 inches thick	15 feet long	B1044.111
			20 feet long	B1044.112
			30 feet long	B1044.113
Reinforced Concrete Moment Frame	Flat slab without shear reinforcement at columns	$0 < V_g/V_0 < 0.2$	No continuity reinforcement	B1049.001a
			With continuity reinforcement	B1049.001b
		$0.2 \leq V_g/V_0 < 0.4$	No continuity reinforcement	B1049.002a
			With continuity reinforcement	B1049.002b
		$0.4 \leq V_g/V_0 < 0.6$	No continuity reinforcement	B1049.003a
			With continuity reinforcement	B1049.003b
	Flat slab with shear reinforcement at columns	$0.2 \leq V_g/V_0 < 0.4$	-	B1049.011
		$0.4 \leq V_g/V_0 < 0.6$	-	B1049.012
	Post-tensioned slab without shear reinforcement at columns	$0.2 \leq V_g/V_0 < 0.4$	No continuity reinforcement	B1049.021a
			With continuity reinforcement	B1049.021b
		$0.4 \leq V_g/V_0 < 0.6$	No continuity reinforcement	B1049.022a
			With continuity reinforcement	B1049.022b
	Post-tensioned slab with shear reinforcement at columns	$0 < V_g/V_0 < 0.4$	-	B1049.031
		$0.4 \leq V_g/V_0 < 0.6$	-	B1049.032
	Flat slab with drop panel or capitol without shear reinforcement at columns	$0 \leq V_g/V_0 < 0.4$	No continuity reinforcement	B1049.041a
			With continuity reinforcement	B1049.041b
		$0.4 \leq V_g/V_0 < 0.6$	No continuity reinforcement	B1049.042a
			With continuity reinforcement	B1049.042b

Table A-3 Masonry Vertical Elements (B105)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/Notes	Fragility Classification Number
Reinforced Masonry Bearing Wall	Partially grouted	Shear dominated	-	B1051.001, B1051.012, B1051.002, B1051.021, B1051.011, B1051.022
		Flexure dominated	-	B1051.003, B1051.023 B1051.004, B1051.024 B1051.013 B1051.014
	Fully grouted	Shear dominated	-	B1052.001, B1052.011 B1052.002, B1052.012
		Flexure dominated	-	B1052.003, B1052.013 B1052.004, B1052.014

Table A-4 Cold-Formed Steel Structural Elements (B106)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/Notes	Fragility Classification Number
Cold-Formed Steel Stud Wall	Wood panel sheathing	Structural sheathing interior	-	B1061.001a
		Stucco finish exterior	-	B1061.001b
	Flat strap × bracing	-	-	B1061.011a
		Stucco finish exterior	-	B1061.011b
	22 mil/31 mil steel sheathing	-	-	B1061.021a
		Stucco finish exterior	-	B1061.021b

Table A-5 Wood Light Frame Structural Elements (B107)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/Notes	Fragility Classification Number
Light Wood Frame Shear Wall	OSB-ply,	No holdowns	-	B1071.001
		Holdowns	-	B1071.021
	OSB-ply, stucco	No holdowns	-	B1071.011
		Holdowns	-	B1071.002
Light Wood Frame, Diagonal Strut Bracing	Diagonal let-in bracing	No holdowns	-	B1071.031
Exterior Wall	Gypsum with wood studs	Fixed below, fixed above		B1071.041

Appendix B

Nonstructural Component Fragility Specifications

Table B-1 Exterior Nonstructural Walls (B201)

Material/System	Construction Design Characteristics	Damage Mode, Design Configuration; Other Features	Other/Comments/ Notes	Fragility Classification Number
Exterior Wall	Gypsum with wood studs	Fixed below, fixed above		B1071.041
Exterior Wall Cold Formed Steel Stud Walls	Wood panel sheathing	Structural Sheathing Interior	-	B2011.001a
		Stucco Finish Exterior	-	B2011.001b
	Flat strap X Bracing	-	-	B2011.011a
		Stucco Finish Exterior	-	B2011.011b
	22 Mil/31 Mil Steel Sheathing	-	-	B2011.021a
		Stucco Finish Exterior	-	B2011.021b
Exterior Wall Light Wood Frame Shear Wall	OSB-ply	No holdowns	-	B2011.101
		Holdowns	-	B2011.121
	OSB-ply, stucco	No holdowns	-	B2011.111
		Holdowns	-	B2011.102
Exterior Wall Light Wood Frame, Diagonal Strut Bracing	Diagonal let-in bracing	No holdowns	-	B2011.131
Exterior Wall Precast Concrete Panels	4.5 inches thick	In-plane deformation		B2011.201a
		Out-of-plane deformation		B2011.201b

Table B-2 Exterior Window Systems (B202)

Basic Type	Configuration	Lamination	Glass Type	Details	Fragility Classification Number
Generic Midrise Stick-Built Curtain wall	Monolithic (single pane)	<i>Not Specified</i>	<i>Not Specified</i>	Aspect ratio = 6:5 Other details <i>Unknown</i>	B2022.001
	Insulating Glass Units (dual pane)	<i>Not Specified</i>	<i>Not Specified</i>	Aspect ratio = 6:5 Other details <i>Unknown</i>	B2022.002
Midrise Stick-Built Curtain Wall	Asymmetric insulating glass units (dual-pane, unequal-thickness IGU)	Laminated (LAM)	Annealed (AN)	1/4 in. (6 mm) inner AN / 1/2 in. (13 mm) outer AN LAM (0.030 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.011
	Monolithic (single pane)	Laminated	Annealed	1/4 in. (6 mm) AN LAM (0.030 PVB); glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.021
				1/4 in. (6 mm) AN laminated, 2-sided SSG, Center Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.022
				1/4 in. (6 mm) AN laminated, 2-sided SSG, Outside Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.023
		Not laminated	Annealed	1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.031
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0 in. (0 mm); aspect ratio = 6:5 sealant = dry	B2022.032
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.13 in. (3 mm); aspect ratio = 6:5 sealant = dry	B2022.033
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.25 in. (6 mm); aspect ratio = 6:5 sealant = dry	B2022.034
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry	B2022.035
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1:2 sealant = dry	B2022.036

Table B-2 Exterior Window Systems (B202) (continued)

Basic Type	Configuration	Lamination	Glass Type	Details	Fragility Classification Number
Midrise Stick-Built Curtain Wall (cont'd)	Monolithic (single pane) (cont'd)	Not laminated (cont'd)	Annealed (cont'd)	1/4 in. (6 mm) AN monolithic, 2-sided SSG, Center Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.037
				1/4 in. (6 mm) AN monolithic, 2-sided SSG, Outside Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.038
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.039
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2:1 sealant = dry	B2022.040
				1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1:2 sealant = dry	B2022.041
			Fully tempered (FT)	1/4 in. (6 mm) FT monolithic, 2-sided SSG, Center Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.051
				1/4 in. (6 mm) FT monolithic, 2-sided SSG, Outside Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.052
				1/4 in. (6 mm) FT monolithic, Seamed Edge; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.053
				1/4 in. (6 mm) FT monolithic, Polished Edge; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.054
			Heat strengthened (HS)	1/4 in. (6 mm) HS monolithic; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.061
	Symmetric insulating glass units (dual-pane, equal-thickness IGU)	Laminated	Annealed	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.030 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.071

Table B-2 Exterior Window Systems (B202) (continued)

Basic Type	Configuration	Lamination	Glass Type	Details	Fragility Classification Number
Midrise Stick-Built Curtain Wall (cont'd)	Symmetric insulating glass units (dual-pane, equal-thickness IGU) (cont'd)	Laminated (cont'd)	Annealed (cont'd)	1/4 in. (6 mm) inner AN / 1/4 in. (6 mm) outer AN LAM (0.060 PVB) IGU; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.072
		Not laminated	Annealed	1 in. (25 mm) AN insulating glass unit (IGU) [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.081
				1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.25 in. (6 mm); aspect ratio = 6:5 sealant = dry	B2022.082
				1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes], 2-sided SSG, Center Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.083
				1 in. (25 mm) AN IGU [1/4 in. (6 mm) inner and outer panes], 2-sided SSG, Outside Panel; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = wet	B2022.084
			Fully tempered	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.091
			Heat strengthened	1 in. (25 mm) HS IGU [1/4 in. (6 mm) inner and outer panes]; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 6:5 sealant = dry	B2022.101
Unitized Curtain Wall (also generic unitized curtain wall)	Symmetric insulating glass units (dual-pane, equal-thickness IGU)	Not laminated	Fully tempered	1-1/4 in. (32 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], 4-sided SSG, VHBTM SGTMM; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = Varies sealant = wet	B2022.201
Generic Storefront	Monolithic (single pane)	Not Specified	Not Specified	Aspect ratio = 6:5 Other details Unknown	B2023.001
	IGU (dual pane)	Not Specified	Not Specified	Aspect ratio = 6.5 Other details Unknown	B2023.002

Table B-2 Exterior Window Systems (B202) (continued)

Basic Type	Configuration	Lamination	Glass Type	Details	Fragility Classification Number
Storefront	Monolithic (single pane)	Laminated	Annealed	1/4 in. (6 mm) AN LAM (0.030 PVB); glass-frame clearance = 0.41 in. (10 mm); aspect ratio = 6:5 sealant = dry	B2023.011
		Not laminated	Annealed	1/4 in. (6 mm) AN monolithic; glass-frame clearance = 0.41 in. (10 mm); aspect ratio = 6:5 sealant = dry	B2023.021
			Fully tempered	3/8 in. (10 mm) FT monolithic, Planar Specimen; glass-frame clearance = 0.5 in. (13 mm); aspect ratio = 1.93:1 sealant = wet	B2023.031
				3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, in-plane; glass-frame clearance = 0.5 in. (13 mm); aspect ratio = 1.93:1 sealant = wet	B2023.032
				3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, combined; glass-frame clearance = 0.5 in. (13 mm); aspect ratio = 1.93:1 sealant = wet	B2023.033
				3/8 in. (10 mm) FT monolithic, Corner Cond. Specimen, Short side; glass-frame clearance = 0.5 in. (13 mm); aspect ratio = 2.72:1 sealant = wet	B2023.034
	Symmetric insulating glass units (dual-pane, equal-thickness IGU)	Not laminated	Annealed	1 in. (25 mm) AN IGU; glass-frame clearance = 0.59 in. (15 mm); aspect ratio = 6:5 sealant = dry	B2023.041
			Fully tempered	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Planar Specimen; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.89:1 sealant = dry	B2023.051
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, in-plane; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.89:1 sealant = dry	B2023.052
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, combined; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.89:1 sealant = dry	B2023.053

Table B-2 Exterior Window Systems (B202) (continued)

Basic Type	Configuration	Lamination	Glass Type	Details	Fragility Classification Number
Storefront (cont'd)	Symmetric insulating glass units (dual-pane, equal-thickness IGU) (cont'd)	Not laminated (cont'd)	Fully tempered (cont'd)	1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, Short side; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2.83:1 sealant = dry	B2023.054
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Planar Specimen; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.88:1 sealant = dry	B2023.055
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, in-plane; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.88:1 sealant = dry	B2023.056
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, combined; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 1.88:1 sealant = dry	B2023.057
				1 in. (25 mm) FT IGU [1/4 in. (6 mm) inner and outer panes], Corner Cond. Specimen, Short side; glass-frame clearance = 0.43 in. (11 mm); aspect ratio = 2.82:1 sealant = dry	B2023.058

Table B-3 Roof Elements (B301, B303, B304)

Item Description	Size	Seismic Installation Condition / Repair Approach	Fragility Classification Number
Roof Tile	N/A	Concrete tiles, secured and compliant with UBC 94	B3011.011
		Clay tiles, secured and compliant with UBC 94	B3011.012
		Concrete tiles unsecured	B3011.013
		Clay tiles unsecured	B3011.014
Masonry Chimneys (unreinforced)	5' above roof	Replace with masonry	B3031.001a
		Replace without masonry	B3031.002a
	10' above roof	Replace with masonry	B3031.001b
		Replace without masonry	B3031.002b
	15' above roof	Replace with masonry	B3031.001c
		Replace without masonry	B3031.002c
Masonry Parapet	N/A	Unreinforced, unbraced	B3041.001

Table B-4 Partitions (C101)

Item Description	Finish	Full or Partial Height	Corner Configuration	Installation Variable	Fragility Classification Number
GWB partition (steel studs, gypsum board both sides)	Paint with taped joints	Full height wallboard	N/A	Fixed below, fixed above	C1011.001a
		Partial height wallboard		Fixed below, laterally braced above	C1011.001b
		Full height wallboard		Fixed below, slip track above with returns	C1011.001c
				Fixed below, slip track above without returns	C1011.001d
GWB partition (wood studs, gypsum board both sides)	Paint with taped joints	Full height wallboard	N/A	Fixed below, fixed above	C1011.011a

Table B-5 Stairs (C201)

Item Description	Type	Seismic installation condition/repair action	Fragility Classification Number
Stair	Prefab steel	With seismic joint	C2011.001a
		No seismic joint	C2011.001b
	Precast concrete	With seismic joint	C2011.011a
		No seismic joint	C2011.011b
	Cast in place concrete	No seismic joint replace with cast in place concrete	C2011.021a
		With seismic joint replace with cast in place concrete	C2011.021b
		No seismic joint replace with steel stair	C2011.021c
		With seismic joint replace with steel stair	C2011.021d
	Hybrid: Steel stringers with precast treads rigidly linked to a stringer	No seismic joint	C2011.031a
		With seismic joint	C2011.031b

Table B-6 Wall Finishes (C301)

Item Description	Finish	Full or Partial Height	Installation Variable	Fragility Classification Number
Wall Finish Applied to One Side of a CWB Partition	Wall paper	Full height	Fixed below, fixed above	C3011.001a
		Partial height	Fixed below, laterally braced above	C3011.001b
		Full height	Fixed Track Below, Slip Track Above with and without Returns	C3011.001c, C3011.001d
	Ceramic tile	Full height	Fixed below, fixed above	C3011.002a
		Partial height	Fixed below, laterally braced above	C3011.002b
		Full height	Fixed Track Below, Slip Track Above with and without Returns	C3011.002c, C3011.002d
	High-end Marble or wood panel	Full height	Fixed below, fixed above	C3011.003a
		Partial height	Fixed below, laterally braced above	C3011.003b
		Full height	Fixed Below, Slip Track Above with and without Returns	C3011.003c, C3011.003d

Table B-7 Floor Finishes, Raised Access Floors, and Floor Flooding (C302)

Item Description	Seismic Installation Condition	Size/Other	Fragility Classification Number
Generic Floor Covering and Wall Damaged by Flooding (Single Pipe Failure)	N/A	Office (Dry)	C3021.001a
		Office (humid)	C3021.001b
		Lab (dry)	C3021.001c
		Lab (humid)	C3021.001d
		Hospital (dry)	C3021.001e
		Hospital (humid)	C3021.001f
		School (dry)	C3021.001g
		School (humid)	C3021.001h
		Apartments (dry)	C3021.001i
		Apartments (humid)	C3021.001j
		Retail (dry)	C3021.001k
		Retail (humid)	C3021.001l
		Warehouse (dry)	C3021.001m
		Warehouse (humid)	C3021.001n
		Hospitality (dry)	C3021.001o
		Hospitality (humid)	C3021.001p
Raised Access Floor	Unanchored, not seismically rated	N/A	C3027.001
	Seismically rated	N/A	C3027.002

Table B-8 Ceilings and Ceiling Lighting (C303)

Item Description	Seismic Installation Condition	Size/Area	Fragility Classification Number
Suspended Ceiling	SDC: A,B Vertical support only	< 250 SF	C3032.001a
		250 – 1000 SF	C3032.001b
		1000 – 2500 SF	C3032.001c
		> 2500 SF	C3032.001d
	SDC C: Vertical support and lateral support for larger ceiling areas	< 250 SF	C3032.002a
		250 – 1000 SF	C3032.002b
		1000 – 2500 SF	C3032.002c
		> 2500 SF	C3032.002d
	SDC D/E: ($I_p = 1.0$) Vertical and lateral support for larger ceiling areas plus wider perimeter angle	< 250 SF	C3032.003a
		250 – 1000 SF	C3032.003b
		1000 – 2500 SF	C3032.003c
		> 2500 SF	C3032.003d
	SDC: D,E,F ($I_p = 1.5$) Same as D/E plus stringent design and installation Q/C	< 250 SF	C3032.004a
		250 – 1000 SF	C3032.004b
		1000 – 2500 SF	C3032.004c
		> 2500 SF	C3032.004d
Independent Pendant Lighting	Not seismically rated		C3034.001
Independent Pendant Lighting	Seismically rated		C3034.002

Table B-9 Elevators and Lifts (D101)

Item Description	Type	Seismic Installation Condition	Fragility Classification Number
Elevator	Traction	Installed in California after 1975, in most western states after 1981 and in most other US States after 1997	D1014.011
	Traction	Installed in California before 1976, in most western states before 1982 and in most other US States before 1998	D1014.012
	Hydraulic	Installed in California after 1975, in most western states after 1981 and in most other US states after 1997	D1014.021
	Hydraulic	Installed in California before 1976, in most western states before 1982 and in most other US States before 1998	D1014.022

Table B-10 Domestic Water Distribution Including Hot Water Heaters(D202)

Item Description	Size	Material Type	Installation Variable	Fragility Classification Number
Cold Water Service, Cold or Hot Potable	Pipe diameter, $\Phi \leq 2.5''$	Threaded Steel	SDC A or B	D2021.011a, D2021.011b
			SDC C	D2021.012a, D2021.012b
			SDC D, E or F	D2021.013a, D2021.013b
			SDC D, E, or F (OSHPP or sim.)	D2021.014a, D2021.014b
Cold Water Service, Cold or Hot Potable	Pipe diameter, $\Phi > 2.5''$	Welded steel	SDC A or B	D2021.021a
			SDC C	D2021.022a
			SDC D, E or F	D2021.023a, D2021.023b
			SDC D, E, or F (OSHPP or sim.)	D2021.024a, D2021.024b
Hot Water Service, Heating Hot Water	Pipe diameter, $\Phi \leq 2.5''$	Threaded steel	SDC A or B	D2022.011a, D2022.011b
			SDC C	D2022.012a, D2022.012b
			SDC D, E or F	D2022.013a, D2022.013b
			SDC D, E, or F (OSHPP or sim.)	D2022.014a, D2022.014b
Hot Water Service, Heating Hot Water	Pipe diameter, $\Phi > 2.5''$	Welded steel	SDC A or B	D2022.021a, D2022.021b
			SDC C	D2022.022a, D2022.022b
			SDC D, E or F	D2022.023a, D2022.023b
			SDC D, E, or F (OSHPP or sim.)	D2022.024a, D2022.024b

Table B-11 Sanitary Waste Piping System (D203)

Item Description	Size	Material Type	Installation Variable	Fragility Classification Number
Sanitary Waste Piping	N/A	Cast iron with flexible couplings	SDC A or B	D2031.011b
			SDC C	D2031.012b
			SDC D, E or F	D2031.013b
			SDC D, E, or F (OSHPPD or sim.)	D2031.014b
		Cast iron with bell and spigot couplings	SDC A or B	D2031.021a, D2031.021b
			SDC C	D2031.022a, D2031.022b
			SDC D, E or F	D2031.023a, D2031.023b
			SDC D, E, or F (OSHPPD or sim.)	D2031.024a, D2031.024b

Table B-12 Chilled Water Piping (D205)

Item Description	Size	Material Type	Installation Variable	Fragility Classification Number
Chilled Water Piping	$\Phi \leq 2.5''$	Threaded steel	SDC A or B	D2051.011a, D2051.011b
			SDC C	D2051.012a, D2051.012b
			SDC D, E or F	D2051.013a, D2051.013b
			SDC D, E, or F (OSHPPD or sim.)	D2051.014a, D2051.014b
Chilled Water Piping	$\Phi > 2.5''$	Welded steel	SDC A or B	D2051.021a, D2051.021b
			SDC C	D2051.022a, D2051.022b
			SDC D, E or F	D2051.023a, D2051.023b
			SDC D, E, or F (OSHPPD or sim.)	D2051.024a, D2051.024b

Table B-13 Steam Piping (D206)

Item Description	Size	Material Type	Installation Variable	Fragility Classification Number
Steam Piping	$\Phi \leq 2.5''$	Threaded steel	SDC A or B	D2061.011a, D2061.011b
			SDC C	D2061.012a, D2061.012b
			SDC D, E or F	D2061.013a, D2061.013b
			SDC D, E, or F (OSHDP or sim.)	D2061.014a, D2061.014b
	$\Phi > 2.5''$	Welded steel	SDC A or B	D2061.021a, D2061.021b
			SDC C	D2061.022a, D2061.022b
			SDC D, E or F	D2061.023a, D2061.023b
			SDC D, E, or F (OSHDP or sim.)	D2061.024a, D2061.024b

Table B-14 Chillers, Cooling Towers, and Compressors (D303)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Chiller	Unanchored, not isolated	< 100 Ton	Internal damage (ID)	D3031.011a
		100 to < 350 Ton		D3031.011b
		350 to < 750 Ton		D3031.011c
		750 to < 1000 Ton		D3031.011d
	Isolated, not restrained	< 100 Ton	Anchorage failure (AF)	D3031.012a
			Internal damage	D3031.012b
			Simultaneously occurring AF and ID	D3031.012c
		100 to < 350 Ton	Anchorage failure	D3031.012d
			Internal damage	D3031.012e
			Simultaneously occurring AF and ID	D3031.012f
		350 to < 750 Ton	Anchorage failure	D3031.012g
			Internal damage	D3031.012h
			Simultaneously occurring AF and ID	D3031.012i
		750 to < 1000 Ton	Anchorage failure	D3031.012j
			Internal damage	D3031.012k
			Simultaneously occurring AF and ID	D3031.012l
	Hard anchored or isolated and restrained	< 100 Ton	Anchorage failure	D3031.013a
			Internal damage	D3031.013b
			Simultaneously occurring AF and ID	D3031.013c

Table B-14 Chillers, Cooling Towers, and Compressors (D303) (continued)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Chiller (continued)	Hard anchored or isolated and restrained (continued)	100 to < 350 Ton	Anchorage failure	D3031.013d
			Internal damage	D3031.013e
			Simultaneously occurring AF and ID	D3031.013f
		350 to < 750 Ton	Anchorage failure	D3031.013g
			Internal damage	D3031.013h
			Simultaneously occurring AF and ID	D3031.013i
		750 to < 1000 Ton	Anchorage failure	D3031.013j
			Internal damage	D3031.013k
			Simultaneously occurring AF and ID	D3031.013l
Cooling Tower	Unanchored, not isolated	< 100 Ton	Internal damage	D3031.021a
		100 to < 350 Ton		D3031.021b
		350 to < 750 Ton		D3031.021c
		750 to < 1000 Ton		D3031.021d
	Isolated, not restrained	< 100 Ton	Anchorage failure	D3031.022a
		< 100 Ton	Internal damage	D3031.022b
		< 100 Ton	Simultaneously occurring AF and ID	D3031.022c
		100 to < 350 Ton	Anchorage failure	D3031.022d
		100 to < 350 Ton	Internal damage	D3031.022e
		100 to < 350 Ton	Simultaneously occurring AF and ID	D3031.022f
		350 to < 750 Ton	Anchorage failure	D3031.022g
		350 to < 750 Ton	Internal damage	D3031.022h
		350 to < 750 Ton	Simultaneously occurring AF and ID	D3031.022i
		750 to < 1000 Ton	Anchorage failure	D3031.022j
		750 to < 1000 Ton	Internal damage	D3031.022k
		750 to < 1000 Ton	Simultaneously occurring AF and ID	D3031.022l
	Hard anchored or isolated and restrained	< 100 Ton	Anchorage failure	D3031.023a
		< 100 Ton	Internal damage	D3031.023b
		< 100 Ton	Simultaneously occurring AF and ID	D3031.023c
		100 to < 350 Ton	Anchorage failure	D3031.023d
		100 to < 350 Ton	Internal damage	D3031.023e
		100 to < 350 Ton	Simultaneously occurring AF and ID	D3031.023f
		350 to < 750 Ton	Anchorage failure	D3031.023g
		350 to < 750 Ton	Internal Damage	D3031.023h
		350 to < 750 Ton	Simultaneously occurring AF and ID	D3031.023i
		750 to < 1000 Ton	Anchorage failure	D3031.023j
		750 to < 1000 Ton	Internal damage	D3031.023k
		750 to < 1000 Ton	Simultaneously occurring AF and ID	D3031.023l
Compressor	Unanchored, not isolated	Small non medical air supply	Internal damage	D3032.011a
		Large non medical air supply		D3032.011b

Table B-14 Chillers, Cooling Towers, and Compressors (D303) (continued)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Compressor (continued)	Unanchored, not isolated (continued)	Small medical quality air supply		D3032.011c
		Large medical quality air supply		D3032.011d
	Isolated, not restrained	Small non-medical air supply	Anchorage failure	D3032.012a
			Internal damage	D3032.012b
			Simultaneously occurring AF and ID	D3032.012c
		Large non-medical air supply	Anchorage failure	D3032.012d
			Internal damage	D3032.012e
			Simultaneously occurring AF and ID	D3032.012f
		Small medical quality air supply	Anchorage failure	D3032.012g
			Internal damage	D3032.012h
			Simultaneously occurring AF and ID	D3032.012i
		Large medical quality air supply	Anchorage failure	D3032.012j
			Internal damage	D3032.012k
			Simultaneously occurring AF and ID	D3032.012l
	Hard anchored or isolated and restrained	Small non-medical air supply	Anchorage failure	D3032.013a
			Internal damage	D3032.013b
			Simultaneously occurring AF and ID	D3032.013c
		Large non-medical air supply	Anchorage failure	D3032.013d
			Internal damage	D3032.013e
			Simultaneously occurring AF and ID	D3032.013f
		Small medical quality air supply	Anchorage failure	D3032.013g
			Internal damage	D3032.013h
			Simultaneously occurring AF and ID	D3032.013i
		Large medical quality air supply	Anchorage failure	D3032.013j
			Internal damage	D3032.013k
			Simultaneously occurring AF and ID	D3032.013l

Table B-15 Distribution Systems (D304)

Equipment Description	Installation Variables	Size, Material	Seismic Rating, Dominant Damage Mode	Fragility Classification Number
HVAC Fan In Line Fan	Fan independently supported and vibration isolated	N/A	SDC A or B	D3041.001a
			SDC C	D3041.001b
			SDC D, E or F	D3041.001c
			SDC D,E,F (high seismic design) Special Regulation (OSHDP) for HVAC installations	D3041.001d
	Fan independently supported but not on vibration isolated	N/A	SDC A or B	D3041.002a
			SDC C	D3041.002b
			SDC D, E or F	D3041.002c
			SDC D,E,F (high seismic design) Special Regulation (OSHDP) for HVAC installations	D3041.002d
HVAC Ducting	Galvanized Sheet Metal	< 6 SF in cross sectional area	SDC A or B	D3041.011a
			SDC C	D3041.011b
			SDC D, E or F	D3041.011c
			SDC D, E, or F (OSHDP or sim.)	D3041.011d
		≥ 6 SF in cross sectional area	SDC A or B	D3041.012a
			SDC C	D3041.012b
			SDC D, E or F	D3041.012c
			SDC D, E, or F (OSHDP or sim.)	D3041.012d
	Stainless Steel	< 6 SF in cross sectional area	SDC A or B	D3041.021a
			SDC C	D3041.021b
			SDC D, E or F	D3041.021c
			SDC D, E, or F (OSHDP or sim.)	D3041.021d
		≥ 6 SF in cross sectional area	SDC A or B	D3041.022a
			SDC C	D3041.022b
			SDC D, E or F	D3041.022c
			SDC D, E, or F (OSHDP or sim.)	D3041.022d
HVAC drops/diffusers in suspended ceilings	No independent safety wires	N/A	SDC A or B	D3041.031a
			SDC C	D3041.031b
HVAC drops/diffusers without ceilings	Support by ducting only. No independent safety wires	N/A	SDC A or B	D3041.032a
			SDC C	D3041.032b
			SDC D, E or F	D3041.032c
			SDC D, E, or F (OSHDP or sim.)	D3041.032d

Table B-15 Distribution Systems (D304) (continued)

Equipment Description	Installation Variables	Size, Material	Seismic Rating, Dominant Damage Mode	Fragility Classification Number
Variable Air Volume (VAV) Box with in-line coil	N/A	N/A	SDC A or B	D3041.041a
			SDC C	D3041.041b
HVAC Fan	Unanchored, not isolated	N/A	Internal damage	D3041.101a
	Isolated, not restrained	N/A	Anchorage failure	D3041.102a
			Internal damage	D3041.102b
			Simultaneously occurring AF and ID	D3041.102c
	Hard anchored or isolated and restrained	N/A	Anchorage failure	D3041.103a
			Internal damage	D3041.103b
			Simultaneously occurring AF and ID	D3041.103c

Table B-16 Packaged Air Handling Units (D305)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Packaged Air Handling Unit	Unanchored, not isolated	< 5000 CFM	Internal damage	D3052.011a
		5000 to < 10000 CFM		D3052.011b
		10000 to < 25000 CFM		D3052.011c
		25000 to < 40000 CFM		D3052.011d
	Hard anchored or isolated and restrained	< 5000 CFM	Anchorage failure	D3052.013a
			Internal damage	D3052.013b
			Simultaneously occurring AF and ID	D3052.013c
		5000 to < 10000 CFM	Anchorage failure	D3052.013d
			Internal damage	D3052.013e
			Simultaneously occurring AF and ID	D3052.013f
		10000 to < 25000 CFM	Anchorage failure	D3052.013g
			Internal damage	D3052.013h
			Simultaneously occurring AF and ID	D3052.013i
		25000 to < 40000 CFM	Anchorage failure	D3052.013j
			Internal damage	D3052.013k
			Simultaneously occurring AF and ID	D3052.013l

Table B-17 Control Panels and Instrumentation (D306)

Equipment Description	Installation variables	Dominant Damage Mode	Fragility Classification Number
Control Panel	Unanchored	Internal Damage	D3067.011a
	Hard anchored	Anchorage failure	D3067.013a
		Internal Damage	D3067.013b
		Simultaneously occurring AF & ID	D3067.013c

Table B-18 Fire Protection (D401)

Item Description	Size	Material Type	Installation Variable	Fragility Classification Number
Fire Sprinkler Water Piping – Horizontal Mains and Branches	N/A	New style Victaulic, threaded steel	SDC A or B	D4011.011a, D4011.011b
			SDC C	D4011.012a, D4011.012b
			SDC D, E or F	D4011.013a, D4011.013b
			SDC D, E, or F (OSHPPD or sim.)	D4011.014a, D4011.014b
		Old style Victaulic, thin-wall steel	SDC A or B	D4011.021a
			SDC C	D4011.022a
			SDC D, E or F	D4011.023a
			SDC D, E, or F (OSHPPD or sim.)	D4011.024a
Fire Sprinkler Drop	6 ft. long drop max. standard steel threaded	Soft unbraced lay-in tile ceiling	Dropping into tile SOFT ceiling, SDC A or B	D4011.031a
			Dropping into lay-in tile SOFT ceiling, SDC C	D4011.032a
			Dropping into lay-in tile SOFT ceiling, SDC D, E or F	D4011.033a
			Dropping into lay-in tile SOFT ceiling, SDC D, E, or F (OSHPPD or sim.)	D4011.034a
		Hard unbraced lay-in tile ceiling	Dropping into lay-in tile HARD ceiling, SDC A or B	D4011.041a
			Dropping into lay-in tile HARD ceiling, SDC C	D4011.042a
		Braced lay-in tile ceiling	Dropping into lay-in tile SOFT ceiling, SDC D, E, or F	D4011.053a
			Dropping into lay-in tile SOFT ceiling, SDC D, E, or F (OSHPPD or sim.)	D4011.054a
			Dropping into lay-in tile HARD ceiling, SDC D, E, or F	D4011.063a
			Dropping into lay-in tile HARD ceiling, SDC D, E, or F (OSHPPD or sim.)	D4011.064a
		No ceiling	No Ceiling, SDC A or B	D4011.071a
			No Ceiling, SDC C	D4011.072a
			No Ceiling, SDC D, E or F	D4011.073a
			No Ceiling, SDC D, E, or F (OSHPPD or sim.)	D4011.074a

Table B-19 Electrical Service and Distribution (D501)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Transformer/ Primary Service	Unanchored	< 100 kVA	Internal damage	D5011.011a
		100 to < 350 kVA		D5011.011b
		350 to < 750 kVA		D5011.011c
		750 to 1500 kVA		D5011.011d
	Hard anchored	< 100 kVA	Anchorage failure	D5011.013a
			Internal damage	D5011.013b
			Simultaneously occurring AF and ID	D5011.013c
		100 to < 350 kVA	Anchorage failure	D5011.013d
			Internal damage	D5011.013e
			Simultaneously occurring AF and ID	D5011.013f
		350 to < 750 kVA 350 to < 750 kVA	Anchorage failure	D5011.013g
			Internal damage	D5011.013h
			Simultaneously occurring AF and ID	D5011.013i
		750 to 1500 kVA	Anchorage failure	D5011.013j
			Internal damage	D5011.013k
			Simultaneously occurring AF and ID	D5011.013l
Motor Control Center	Unanchored	N/A		D5012.013a
	Hard anchored	N/A	Anchorage failure	D5012.013b
				D5012.013c
				D5012.013d
Low Voltage Switchgear	Unanchored	100 to < 350 Amp	Internal damage	D5012.021a
		350 to < 750 Amp		D5012.021b
		750 to < 1200 Amp		D5012.021c
		1200 to 2000 Amp		D5012.021d
	Hard anchored	100 to < 350 Amp	Anchorage failure	D5012.023a
			Internal damage	D5012.023b
			Simultaneously occurring AF and ID	D5012.023c
		350 to < 750 Amp	Anchorage failure	D5012.023d
			Internal damage	D5012.023e
			Simultaneously occurring AF and ID	D5012.023f
		750 to < 1200 Amp	Anchorage failure	D5012.023g
			Internal damage	D5012.023h
			Simultaneously occurring AF and ID	D5012.023i
		1200 to 2000 Amp	Anchorage failure	D5012.023j
			Internal damage	D5012.023k
			Simultaneously occurring AF and ID	D5012.023l

Table B-19 Electrical Service and Distribution (D501) (continued)

Equipment Description	Installation variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Distribution Panel	Unanchored, not isolated	100 to < 350 Amp	Internal damage	D5012.031a
		350 to < 750 Amp		D5012.031b
		750 to < 1200 Amp		D5012.031c
		1200 to 2000 Amp		D5012.031d
	Hard anchored	100 to < 350 Amp	Anchorage failure	D5012.033a
			Internal damage	D5012.033b
			Simultaneously occurring AF and ID	D5012.033c
		350 to < 750 Amp	Anchorage failure	D5012.033d
			Internal damage	D5012.033e
			Simultaneously occurring AF and ID	D5012.033f
		750 to < 1200 Amp	Anchorage failure	D5012.033g
			Internal damage	D5012.033h
			Simultaneously occurring AF and ID	D5012.033i
		1200 to 2000 Amp	Anchorage failure	D5012.033j
			Internal damage	D5012.033k
			Simultaneously occurring AF and ID	D5012.033l

Table B-20 Other Electrical Systems (D509)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Battery Rack	Unanchored	N/A	Internal damage	D5092.011a
	Hard anchored		Anchorage failure	D5092.013a
			Internal damage	D5092.013b
			Simultaneously occurring AF and ID	D5092.013c
Battery Charger	Unanchored	N/A	Internal damage	D5092.021a
	Hard anchored		Anchorage failure	D5092.023a
			Internal damage	D5092.023b
			Simultaneously occurring AF and ID	D5092.023c
Diesel Generator	Unanchored, not isolated	100 to < 350 kVA	Internal damage	D5092.031a
		350 to < 750 kVA		D5092.031b
		750 to 1200 kVA		D5092.031c
		1200 to 2000 kVa		D5092.031d
	Isolated, not restrained	100 to < 350 kVA	Anchorage failure	D5092.032a
			Internal damage	D5092.032b
			Simultaneously occurring AF and ID	D5092.032c
		350 to < 750 kVA	Anchorage failure	D5092.032d
			Internal damage	D5092.032e
			Simultaneously occurring AF and ID	D5092.032f
		750 to 1200 kVA	Anchorage failure	D5092.032g
			Internal damage	D5092.032h
			Simultaneously occurring AF and ID	D5092.032i

Table B-20 Other Electrical Systems (D509) (continued)

Equipment Description	Installation Variables	Size or Rated Capacity	Dominant Damage Mode	Fragility Classification Number
Diesel Generator (cont'd)	Isolated, not restrained (cont'd)	1200 to 2000 kVa	Anchorage failure	D5092.032j
			Internal damage	D5092.032k
			Simultaneously occurring AF and ID	D5092.032l
	Hard anchored or isolated and restrained	100 to < 350 kVA	Anchorage failure	D5092.033a
			Internal damage	D5092.033b
			Simultaneously occurring AF and ID	D5092.033c
		350 to < 750 kVA	Anchorage failure	D5092.033d
			Internal damage	D5092.033e
			Simultaneously occurring AF and ID	D5092.033f
		750 to 1200 kVA	Anchorage failure	D5092.033g
			Internal damage	D5092.033h
			Simultaneously occurring AF and ID	D5092.033i
		1200 to 2000 kVa	Anchorage failure	D5092.033j
			Internal damage	D5092.033k
			Simultaneously occurring AF and ID	D5092.033l

Table B-21 Movable Furnishing (E202)

Item Description	Size	Seismic Installation Condition	Fragility Classification Number
Modular workstation	N/A	N/A	E2022.001
Unsecured fragile objects on shelves	N/A	Unknown	E2022.010
Fragile contents	N/A	Secured by museum putty, or other weak but sticky stuff	E2022.011
Fragile contents on shelves	N/A	In storage cabinets with latches	E2022.012
Unsecured fragile objects on shelves	N/A	Low friction surface	E2022.013
Home entertainment equipment on shelves	N/A	Unknown or average	E2022.020
Electronic Equipment on wall mount brackets	N/A	On wall mount brackets	E2022.021
Desktop Electronics including computers, monitors, stereos, etc.	N/A	On slip-resistant surface	E2022.022
	N/A	On smooth surface	E2022.023
Bookcase	2 shelves	Unanchored	E2022.102a
		Anchored	E2022.102b
	3 shelves	Unanchored	E2022.103a
		Anchored	E2022.103b
	4 shelves	Unanchored	E2022.104a

Table B-21 Movable Furnishing (E202)

Item Description	Size	Seismic Installation Condition	Fragility Classification Number
Bookcase (cont'd)	5 shelves	Unanchored	E2022.105a
		Anchored	E2022.105b
	6 shelves	Unanchored	E2022.106a
		Anchored	E2022.106b
Vertical Filing Cabinet	2 drawer	Unanchored	E2022.112a
		Anchored	E2022.112b
	4 drawer	Unanchored	E2022.114a
		Anchored	E2022.114b
Lateral Filing Cabinet	4 drawer	Unanchored	E2022.124a
		Anchored	E2022.124b
	5 drawer	Unanchored	E2022.125a
		Anchored	E2022.125b

Table B-22 Special Structures (F101)

Item Description	Size	Seismic Installation Condition	Fragility Classification Number
Storage rack	3-5 levels, 14.5-20 ft high	Comply with Rack Manufacturing Institute Seismic Provisions Prior to 2007 Edition	F1012.001

C.1 Introduction

The *Performance Assessment Calculation Tool* (PACT) provided in Volume 3 is the computational companion to Volume 1. PACT provides a user-friendly platform for scenario-based, intensity-based, and time-based loss calculations. It can accommodate results obtained from nonlinear response history analyses as well as simplified analyses.

PACT provides three basic but integrated functions:

1. Gathering and organizing building information, fragility functions, and demand parameters;
2. Performing loss calculations including repair cost, downtime, and casualty estimates; and
3. Providing overall and performance group specific loss information obtained from the above calculations.

PACT and its associated data management utilities (i.e., the **Fragility Specification Manager** and **Building Population Modeler**) are coded in Microsoft C#.net software development platform.

In this Second Edition, PACT has been enhanced to include an algorithm for environmental impact assessment. Further details about the methodology and its development are provided in FEMA P-58-3 BD 3.7.20.

C.2 Hardware and Software Requirements

A computer with the following minimum software and hardware are necessary to use PACT:

- Microsoft Windows 2000, NT, XP, Vista, or 7 operating system
- 200 MB of available hard disk
- A Pentium 500 MHz or faster central processing unit (CPU)
- 256 MB of RAM
- A monitor with a minimum of 800×600 pixels resolution

Only one commercial third party control is used (for creating graphs) and PACT users do not need to license any software or utilities in order to use PACT. Those who want to modify the code or further develop PACT need to license only one third party control.

C.3 Installing PACT

PACT is provided as a single file installation executable, version 3.1.2, in Volume 3. The setup program will guide through the installation when double clicked.

PACT requires the free Microsoft Net Framework 3.5 to be installed on the computer. Most newer computers have this utility installed as a part of their operating system. However, the PACT installer checks the computer for presence of the Microsoft Net Framework 3.5 and if necessary it will download it from the Microsoft website and install it. Therefore, internet connectivity during the PACT installation process is prudent.

Once the installation is completed, a shortcut to PACT is placed the desktop as shown in Figure C-1.



Figure C-1 PACT shortcut icon.

It is recommended that users run PACT as an Administrator. To do this, right click on the PACT icon and select “Run as Administrator.”

C.4 PACT Control Panel

When PACT is started, the **PACT Control Panel** appears. This is the focal point of activities when the program is used. The user will come back to this panel before and after completion of each major task.

The basic PACT operations are grouped together. They are:

- Model the building and import analyses results
- Evaluate performance, and
- Examine results.

The two PACT utilities that can be operated either within PACT or as totally independent functions are:

- Fragility Specification Manager, and
- Building Population Modeler.

The Reporting option allows generation of Microsoft Word reports.

Finally, the Exit button terminates PACT operation.

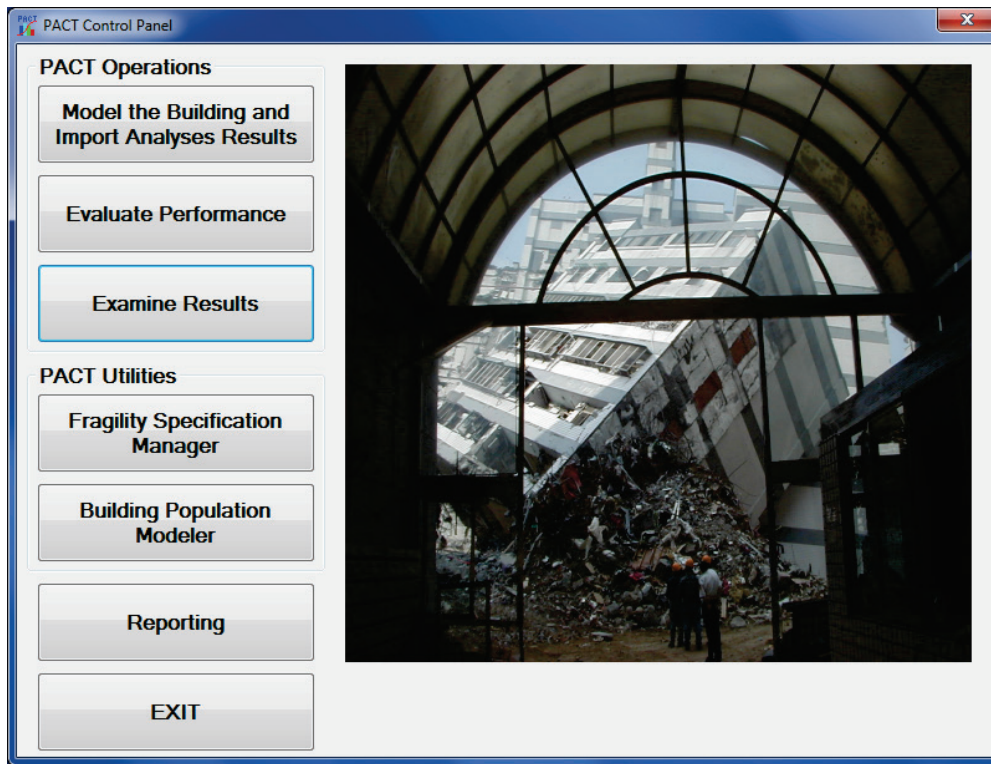


Figure C-2 PACT Control Panel.

C.5 Model the Building and Import Analyses Results

Selection of the **Model the Building and Import Analyses Results** button initiates the **Building Modeler** window where the building, its contents, results of structural analyses are defined, as shown in Figure C-3.

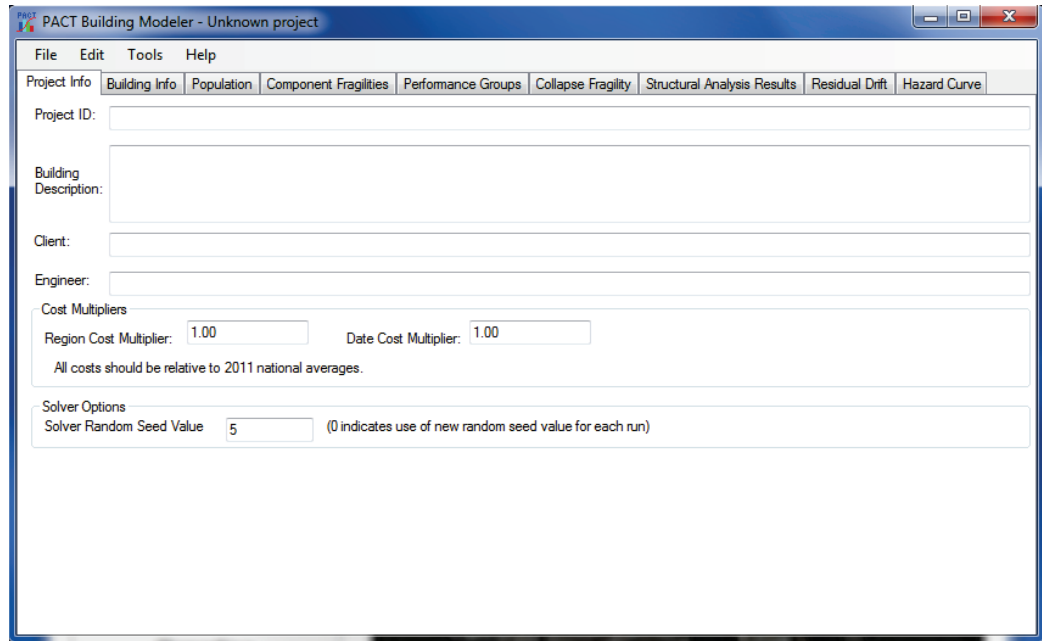


Figure C-3 PACT Building Modeler window.

C.5.1 Building Modeler Menus

PACT initially displays a blank canvas assuming that a new performance assessment model is started from scratch. Figure C-4 illustrates how to retrieve existing PACT performance assessment models.

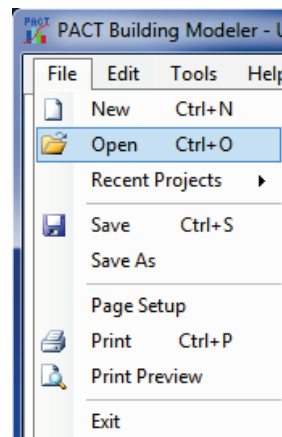


Figure C-4 File menu.

A default five story office building model is built into PACT and can be retrieved as shown in Figure C-5. Two versions of the model are provided: One using the nonlinear response history method and the other using the simplified (linear) method.

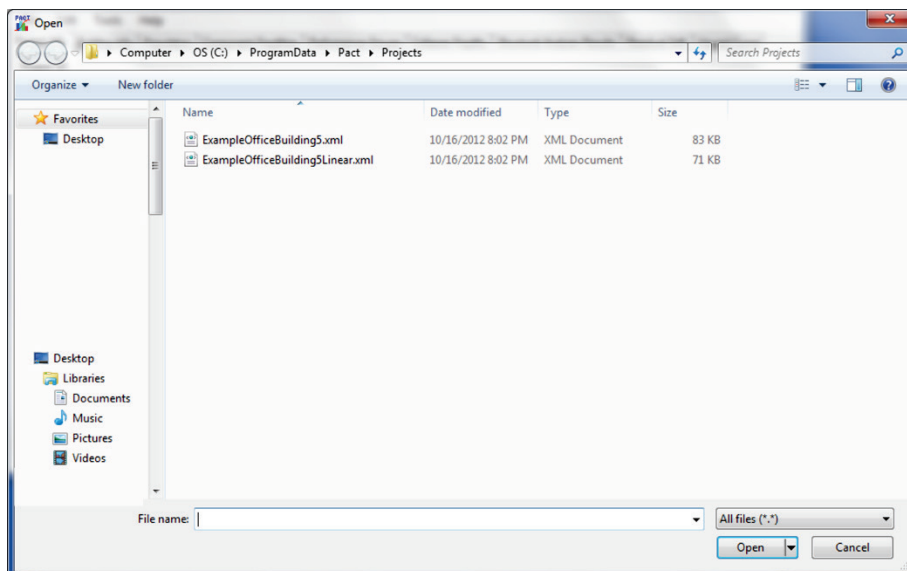


Figure C-5 Open File menu.

Once an existing PACT file is opened, the blank fields are overwritten by the relevant information contained in the opened file.

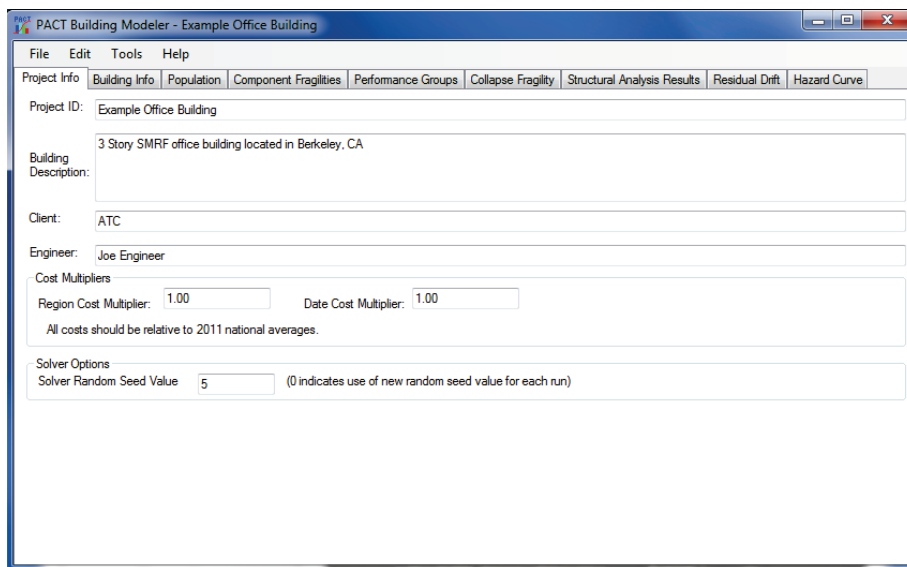


Figure C-6 Project Information tab with retrieved data from opened file.

Under the *File* Menu, *New* command can be used to start a new project from scratch, *Recent Projects* to see a list of projects you have worked on recently, *Save* to save the project under its current name, and *Save As* to save a copy of the project under a new name. On occasion, this action may set all demands to zero, so users are encouraged to review the newly created file for completeness. In addition, *Page Setup* can be used to setup a printer and print preferences, *Print* to print a copy of the form displayed on the screen, and *Print Review* to see how the selection would look. Finally, *Exit*

command would terminate the **Building Modeler** and return to the **Control Panel**.

Under the *Edit* menu, shown in Figure C-7 *Cut*, *Copy*, *Paste*, and *Select All* commands can be used to cut and paste contents of one or several cells. This can be used to cut and paste results of analyses from a spreadsheet program like Excel or tables contained in a word processing program such as Word.

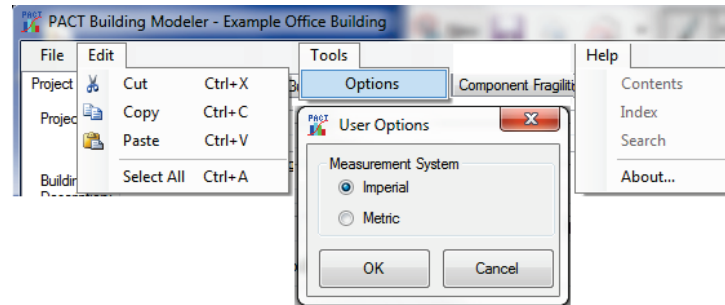


Figure C-7 Edit, Tools, and Help menus.

Under the *Tools* Menu, *Options* allows for switching between imperial and metric units. PACT is unit independent and both units are accommodated.

C.5.2 Project Information Tab

This tab, shown in Figure C-6, contains input fields for project identification, building description, and client and engineer identifications. In addition, regional and date cost multipliers for the project are to be entered here. Note that PACT cost estimates are based on the 2011 Northern California average costs. The user may choose to use a multiplier based on the year the evaluation is being run and the region where the building is located.

Since performance assessment with PACT involves generation of a multitude of random numbers, in order to get exactly the same result each time the program is executed for the same building, the same solver random seed value should be used. Otherwise, results that are very close but are not necessarily identical to those obtained from previous executions of the program will be output. Putting in a value of zero will mean that the program will generate a new random seed every time the results are calculated.

C.5.3 Building Information Tab

This tab, shown in Figure C-8, contains input fields for adding, editing, and reviewing basic building information such as number of stories, total replacement cost and time, core and shell replacement cost, maximum number of workers per unit floor area (needed for estimating repair time),

total loss threshold as a fraction of total replacement cost, and carbon emissions and embodied energy replacement values.

Floor Num	Floor Name	Story Height (ft.)	Area (sq. ft.)	Height Factor	Hazmat Factor	Occupancy Factor
1	Floor 1	11.50	22,736.00	1	1	1
2	Floor 2	11.50	22,736.00	1	1	1
3	Floor 3	11.50	22,736.00	1	1	1
4	Floor 2		22,736.00	1	1	1

Figure C-8 Building Information tab.

Filling the **Most Typical Default Values** for floor area and story height populates these values in the table shown in the lower part of the form. At any time, the tabulated values in the table can be changed by clicking on the corresponding cell. For example, if a 10-story building has a first floor height of 20 ft, second floor height of 16 ft, and all other floors are 13.5 ft high each, then 13.5 ft will be entered as the most typical height and consequently the column will be populated with 13.5 ft. The user can then change the values for the first two floors manually.

Each floor can be assigned a custom name. This will have no effect on the building logic, but will show up in the reports and output, making the basement and roof floors easier to distinguish.

Height Factor, Hazmat Factor, and Occupancy Factor values for each floor can also be entered here. The costs of all damaged items on each floor will be multiplied by these three cost factors.

C.5.4 Population Tab

The **Population** tab, shown in Figure C-9 is divided into three separate windows. In the first one, the most typical population models for the building and the fraction of floor area that they apply to are selected. For

example, if the typical floor of the building consists of 80% commercial office space and 20% retail space, on the first row Commercial Office should be selected for **Occupancy** with 0.8 **Fraction** on the same row and then the second row will be filled with Retail and 0.2.

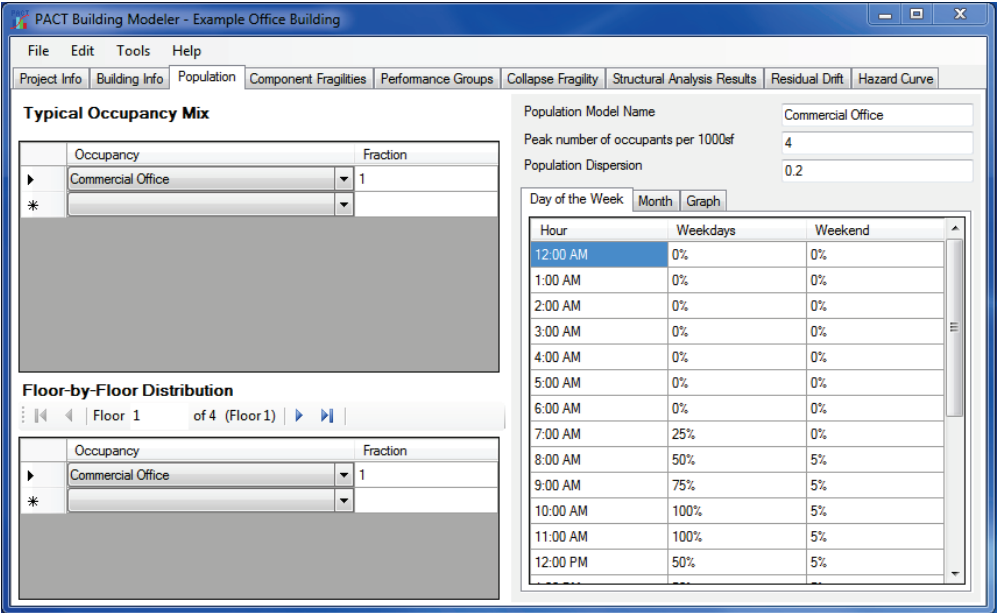


Figure C-9 Population tab.

Default population models, presented on the right side of the form for this particular project, can also be easily edited. Note, however, that if changes are made to the population models, these changes will be saved for this project only and will not change the values stored in the **Building Population Modeler** utility. Eight population models are provided with PACT in the **Building Population Modeler** utility, additional population models can be added.

The values entered on the upper left of the window as typical values are automatically applied to all floors except the roof. The dropdown list and arrows on the bottom left window can be used to change these values for each floor by moving from one floor to another using the floor arrows.

The information corresponding to the selected population model is shown on the right window. Population distribution per month, day of the week, and hour of the day may be viewed in tabular or graphical form, as shown in Figure C-10.

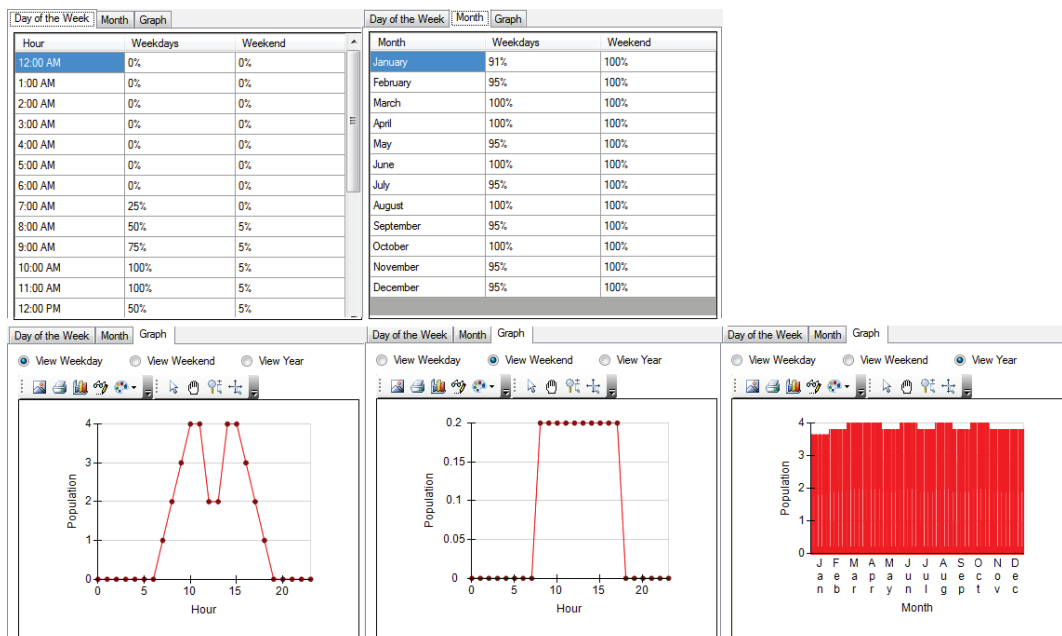


Figure C-10 Population model data screens.

A variety of icons are displayed above PACT graphs and charts and aid in copying, exporting, printing, changing, and customizing how graphs are presented, printed and saved.


C.5.5 Component Fragilities Tab






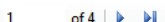
The **Component Fragilities** tab is organized in two parts, as shown in Figure C-11. The top half is used to identify the most typical fragility specifications to be included in the model of the building and the horizontal directions they apply to. The population model corresponding to the selected fragility specification need also be input here. If the same fragility specification is present at more than one place in the structure, the fragility function needs to be repeated so that there is one for each of the population models that apply to that fragility specification.

On the bottom half of the window, the list is copied to all floors. The dropdown list and arrows can be used to add, remove, or change the fragility specifications at each floor floors.

Figure C-11 Component Fragilities tab.

C.5.6 Performance Groups Tab

Once the fragility specifications are selected on the **Component Fragilities** tab, the **Performance Groups** tab, shown in Figure C-12, is used to furnish PACT with the relevant quantities and other needed information. First, the table should be populated with the selected fragility specifications in the previous tab using the  button on the righthand side.

Different directions and floors can be navigated to by using the    and    buttons. If there is uncertainty about the quantities (for example, number of desktop computers at a floor), an appropriate **Quantity Dispersion** can be specified. The default **Fragility Correlated** flag assigned to each fragility specification can be changed by checking or unchecking the corresponding box. Note, however, that making fragilities uncorrelated may substantially increase

execution time. The population model applicable to each performance group can be changed if more than one population model is utilized in the building.

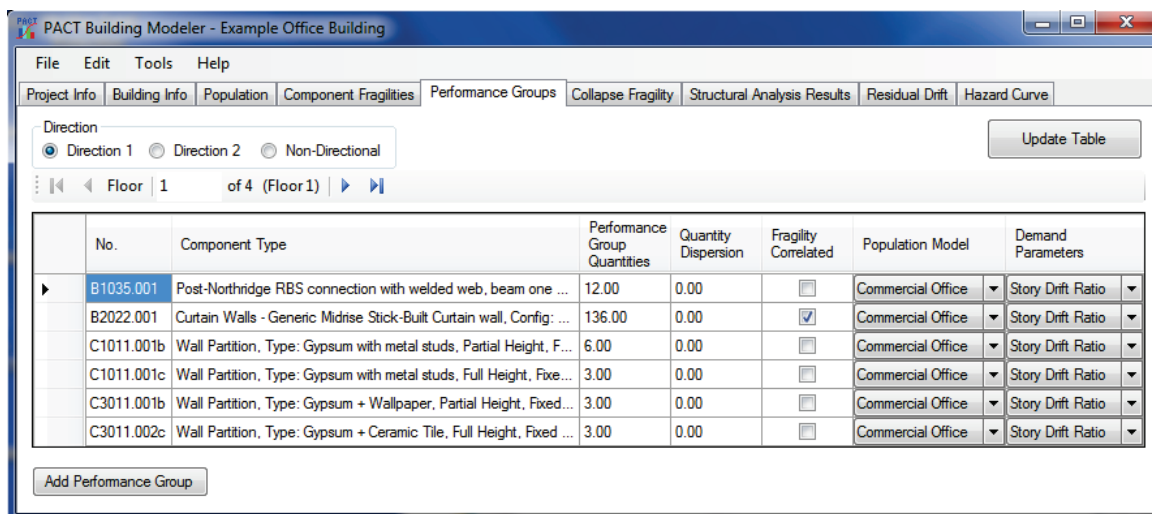


Figure C-12 Performance Groups tab.

In addition to the commonly used engineering demand parameters (EDP), such as story drift ratio and floor acceleration, the user can also specify special or custom demand parameters. For example, if the fragility function for door frames is defined by doors jamming if residual drift exceeds a certain value, residual drift ratio can be defined as a new Special EDP, as shown in Figure C-13. This will prompt for residual drift ratio values in addition to other demand parameters.

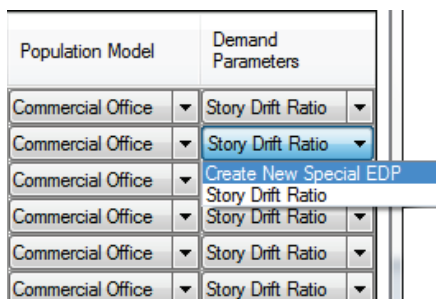


Figure C-13 Demand parameter selection data block.

If one or more fragility specifications were not entered in the **Component Fragilities** tab, they may be directly added to selected performance groups using **Add Performance Group** button at the lower left.

C.5.7 Collapse Fragility Tab

The **Collapse Fragility** tab is used to model structural collapse and its consequences. If potential collapse is not necessary in the building assessment, the corresponding box at the top of Figure C-14 can be

unchecked. Collapse fragility is defined in terms of the median spectral acceleration, g , at the fundamental period of structure that can cause structural collapse and the associated dispersion. At least one collapse mode needs to be defined, but there is no upper limit on the number of collapse modes that can be included. In addition, the mutually exclusive probability of collapse in each mode conditioned on collapse occurring, is also entered. The fraction of each floor affected by a collapse is specified in a table. For example, Figure C-14 shows three collapse modes representing total collapse, soft story collapse, and middle floor collapse are selected.

Once the collapse modes are defined, the arrows in the **Collapse Consequences** data block are used to cycle through modes and define the consequences of occurrence of each mode including the fatality and injury rates per floor and the corresponding dispersions. For example, in Figure C-14, the mean fatality rate of 0.90 means that if this type of collapse occurs, 90% of the floor occupants at the time of the event will be perished.

PACT Building Modeler - Example Office Building

File Edit Tools Help

Project Info Building Info Population Component Fragilities Performance Groups Collapse Fragility Structural Analysis Results Residual Drift Hazard Curve

☒ Include Potential Collapse in Assessment

Collapse Fragility In terms of $S_a(T)$ Median: 1.5 Dispersion: 0.4

Number of Potential Collapse Modes: 3

Mutually Exclusive Probability of Mode Given Collapse

Mode 1	Mode 2	Mode 3
0.6	0.2	0.2

Fraction of Floor Subject to Collapse Debris

Floor	Mode 1	Mode 2	Mode 3
Floor 3 (3)	1	0.1	0.1
Floor 2 (2)	1	0.2	0.8
Floor 1 (1)	1	0.6	0.1

Collapse Consequences

of 3

Floor	Fatality Rate Mean	Fatality Rate COV	Injury Rate Mean	Injury Rate COV
Floor 3 (3)	0.9	0	0.1	0
Floor 2 (2)	0.9	0	0.1	0
Floor 1 (1)	0.9	0	0.1	0

Figure C-14 Collapse Fragility tab.

C.5.8 Structural Analysis Results Tab

The **Structural Analysis Results** tab is used to input results of structural analyses. As shown in Figure C-15, the first input is needed to specify the assessment type. Intensity-based assessments should be conducted if there is an intention of conducting a time-based evaluation down the road. Next, the type of analysis results should be selected: Nonlinear or linear (simplified). For nonlinear analysis, the typical number of demand vectors to import, should be defined, although the number can change for each intensity or

scenario. For simplified analysis, the number of demand vectors is always one (see Figure C-16). The number of realizations that PACT will perform for each intensity/scenario is provided next. Note, that in order to obtain a realistic realization of casualty figures, a rather large number of realizations is needed because PACT assigns a random date and time to each realization affecting the number of people in the building and enough realizations are needed to cover the population distribution of the building during a whole year in a statistically meaningful way.

PACT will automatically determine the non-directional demand parameters by multiplying the maximum value for the two inputted directions by a conversion factor. The conversion factor can be entered here.

For Collapse Only

Floor/Story	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11
Floor 3-Roof (rad)	0.00529	0.006667	0.005652	0.00529	0.007101	0.00587	0.006522	0.006377	0.005217	0.005507	0.007101
Floor 2-3 (rad)	0.005725	0.00587	0.00558	0.005652	0.005435	0.00587	0.005725	0.005362	0.005652	0.00558	0.005725
Floor 1-2 (rad)	0.003155	0.003631	0.00369	0.002976	0.002321	0.003274	0.003214	0.003274	0.003452	0.002857	0.004107

Figure C-15 Structural Analysis Results tab for entry of nonlinear analysis results.

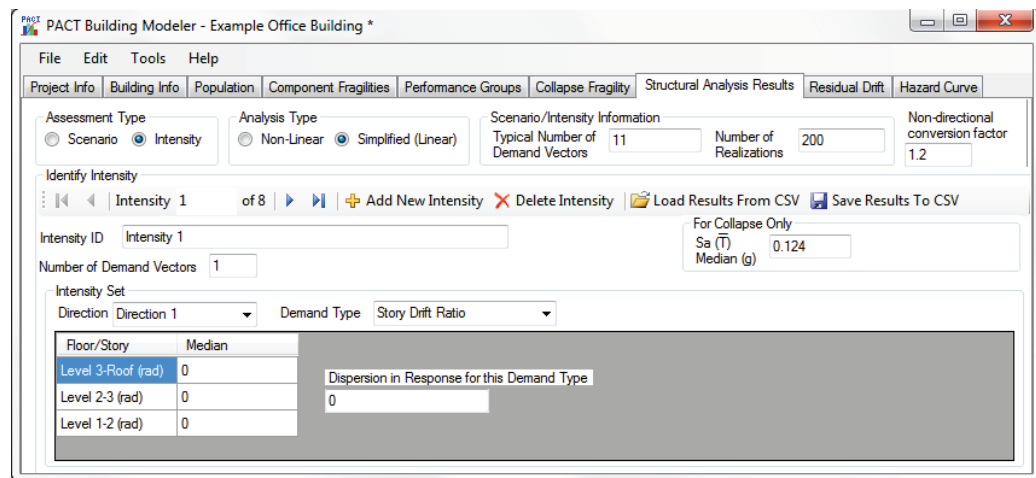



Figure C-16 Structural Analysis Results tab for entry of simplified analysis results.

Under the **Identify Intensity** data block, click  to add as many scenarios/intensities as needed.

For each scenario/intensity, a description for each scenario/intensity should be provided in the space provided for this purpose. If a particular scenario/intensity has a different number of demand vectors than the “Typical” value set above, it can be changed. A modeling dispersion can also be set for each scenario/intensity, as well as spectral acceleration that will be used for calculating collapse probabilities.

The table needs to be filled with the results of analyses for each scenario/intensity in each direction and for each demand parameter. The arrows can be used to cycle through various scenarios/intensities. If an Excel spreadsheet containing this information is created, the data could be cut and paste into the PACT table.

C.5.9 Residual Drift Tab

In the **Residual Drift** tab, a lognormal fragility function for maximum building residual drift ratio, as well as the residual drift ratio results from the nonlinear analysis for each intensity or scenario can be entered. If there is no need to use residual drift calculations, the box at the top of the tab should be unchecked, as shown in Figure C-17.

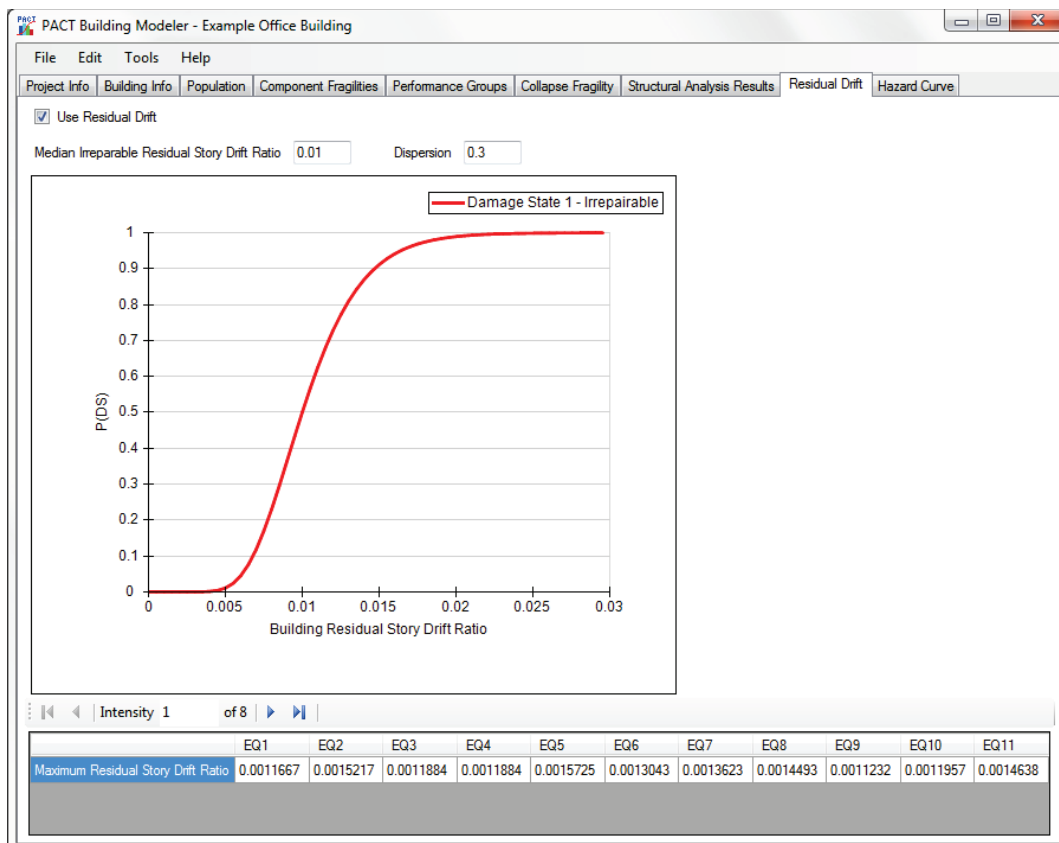


Figure C-17 Residual Drift tab.

C.5.10 Hazard Curve Tab

PACT will transfer the spectral accelerations entered in the previous tab into the hazard curve table contained in the **Hazard Curve** tab, shown in Figure C-18. These values are grayed out so that they cannot be changed here, they can only be changed in the previous tab. Once the mean annual frequency of exceedance (MAFE) values corresponding to each spectral acceleration are entered, the hazard curve will be drawn.

C.5.11 Saving the PACT Model

Once all of the information has been entered in the tabs, the model should be saved under a desired name.

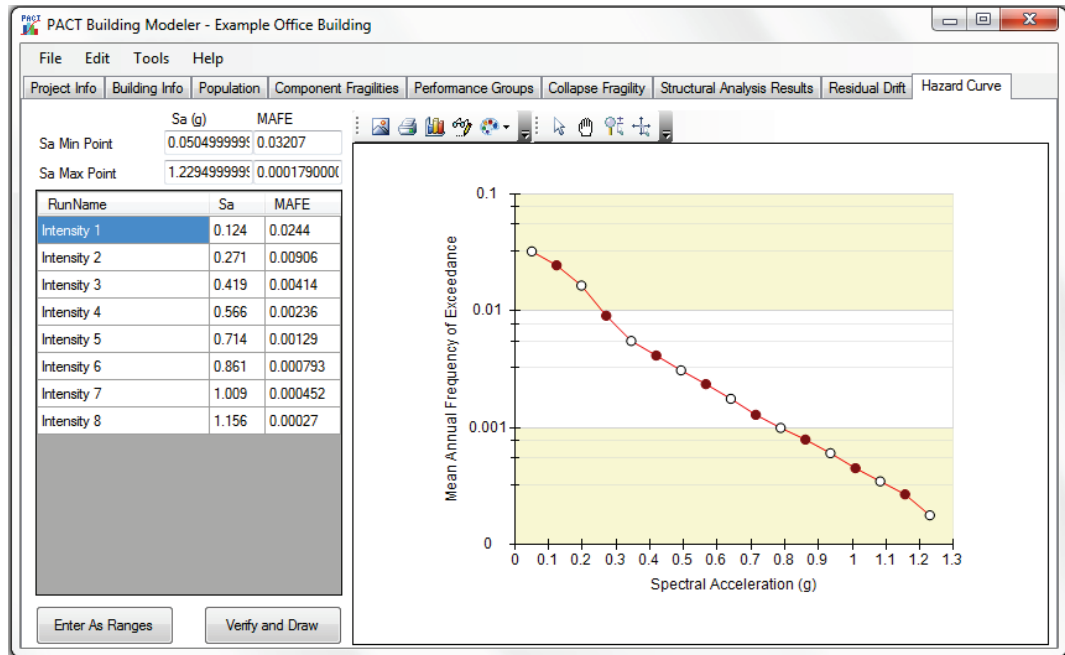


Figure C-18 Hazard Curve tab.

C.6 Evaluate Performance

Once the model has been developed, the Evaluate Performance button is activated in the **PACT Control Panel** and the window shown in Figure C-19 will appear.

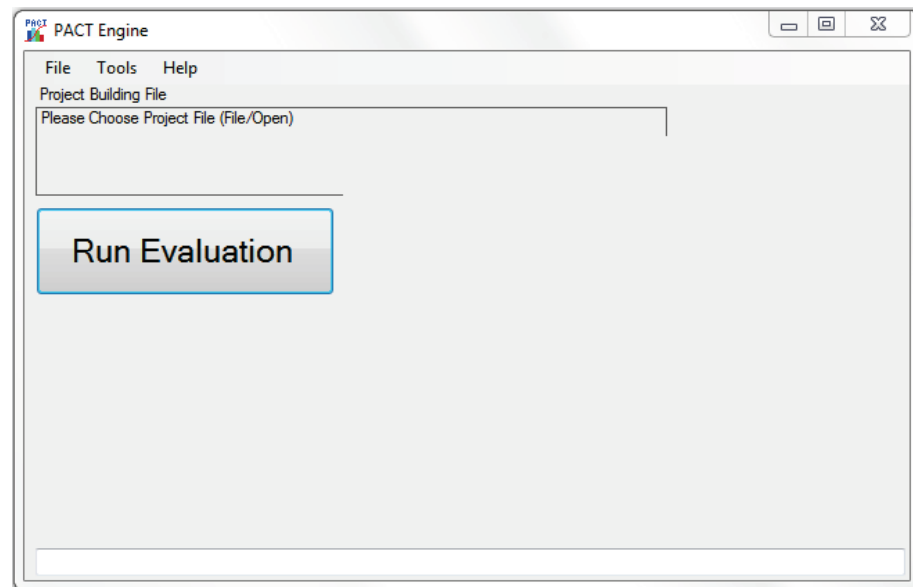


Figure C-19 PACT Engine window.

As illustrated in Figure C-20, from the *File* menu, selecting *Open Building Project* will allow the selection of the desired model. If the computer has a dual- or multi-core processor, selecting the *Use Threading* under the *Options*

menu and clicking *Yes* will utilize the parallel processing capabilities of the computer to speed up the evaluation process.

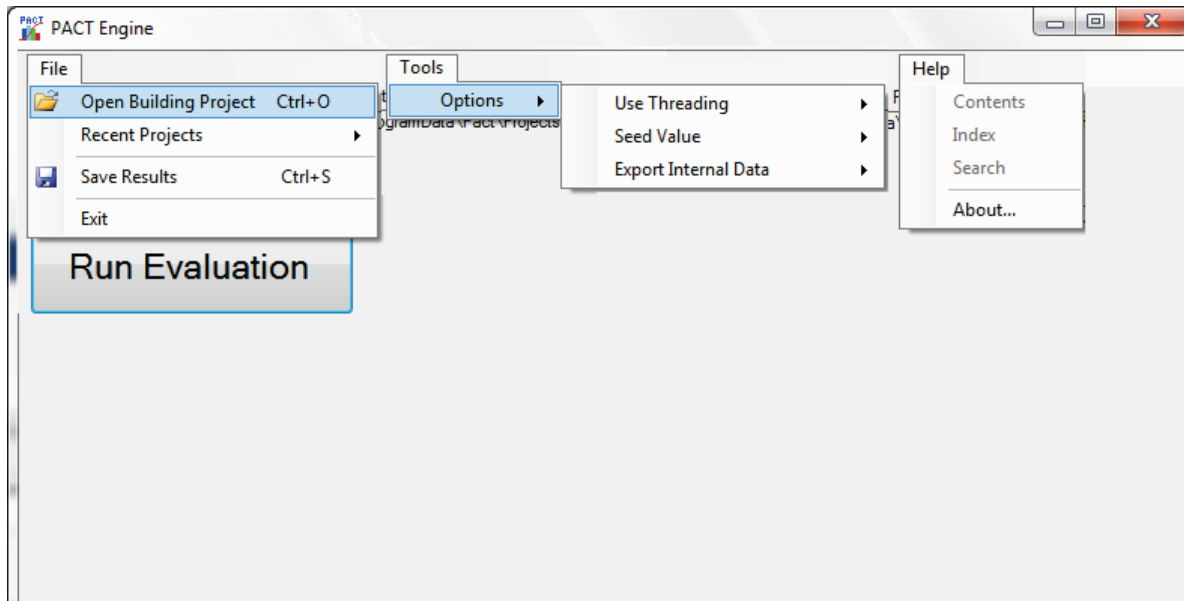


Figure C-20 Analysis options menu.

When the *Run Evaluation* button is clicked, depending on the speed of the computer, the number of realizations selected and whether fragilities are correlated or uncorrelated, the PACT execution time may take anywhere between a few seconds to a number of hours. Progress bars at the bottom of the form indicate the status of operation, as shown in Figure C-21, and upon completion of execution the word “Done” will be displayed.

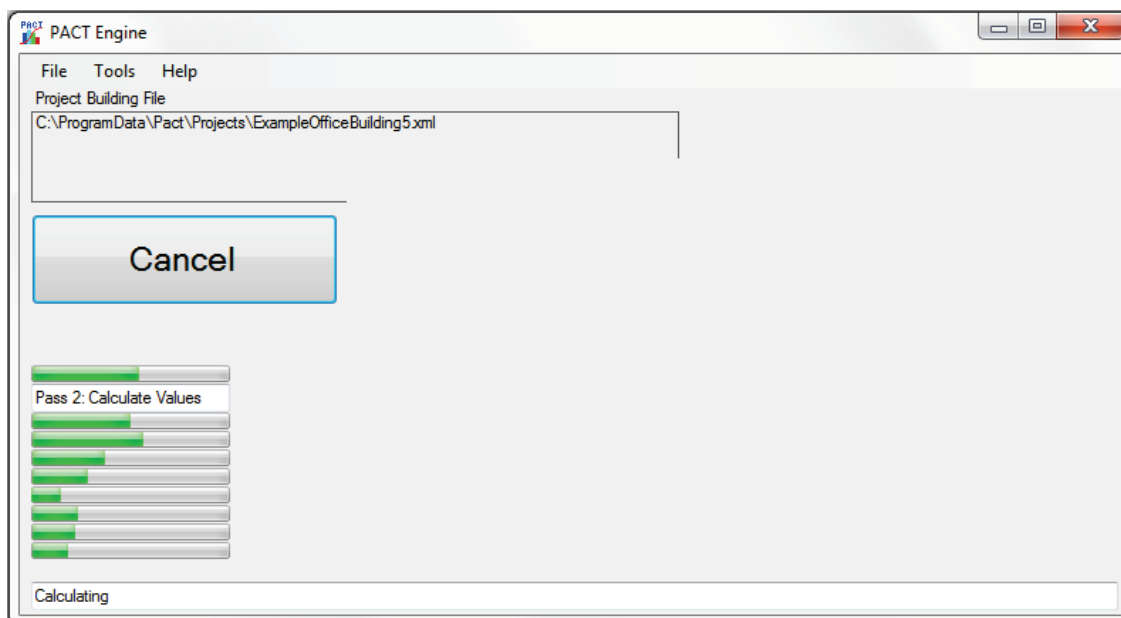


Figure C-21 PACT Engine progress screen.

Upon completion of execution, the results can be evaluated immediately because PACT keeps these results available for viewing as long as the user does not exit from PACT or initiate a new model. The file can also be saved as a .bin file or a .xml file; however, this action may cause out of memory errors.

C.6.1 Command Line Evaluation

There is also a command line version of the PACT Engine. The filename is *PactEngine.exe*, and is located in the main installation directory. This file can be run from the command line, in a batch file, or from an external program. It uses command line switches to change the default options. It will accept multiple input files at one time. The format of the command line is:

`"PactEngine InputFileName(s) -t[+-] -e[cnd] -s -e -d -b"`

The available command line switches are:

- -h: Display the help information
- -t+: Turn multi-threading on
- -t-: Turn multi-threading off
- -s #: Override the seed value
- -e: Export internal data
- -d: Add date/time stamp to output filename
- -b: Save results as a binary formatted file (default is XML format)

The output file will be saved in the same directory as the input file, with the default name of "inputFileName_results.xml," unless the -d option is selected, where it will add the date/time stamp of the analysis to the run, in which case the format will be "InputFileName_results_YYYY-MM-DDTHH.MM.SS.xml" (e.g., InputFileName_results_2011-12-31T14.30.00.xml is Dec 31, 2011, at 2:30 in the afternoon).

If a particular command line switch is not used it will use the default option last selected when using the graphical interface, unless otherwise specified above.

C.7 Examine Results

Once the engine has run, the **Examine Results** button is activated in the **PACT Control Panel** and the window shown in Figure C-22 will appear.

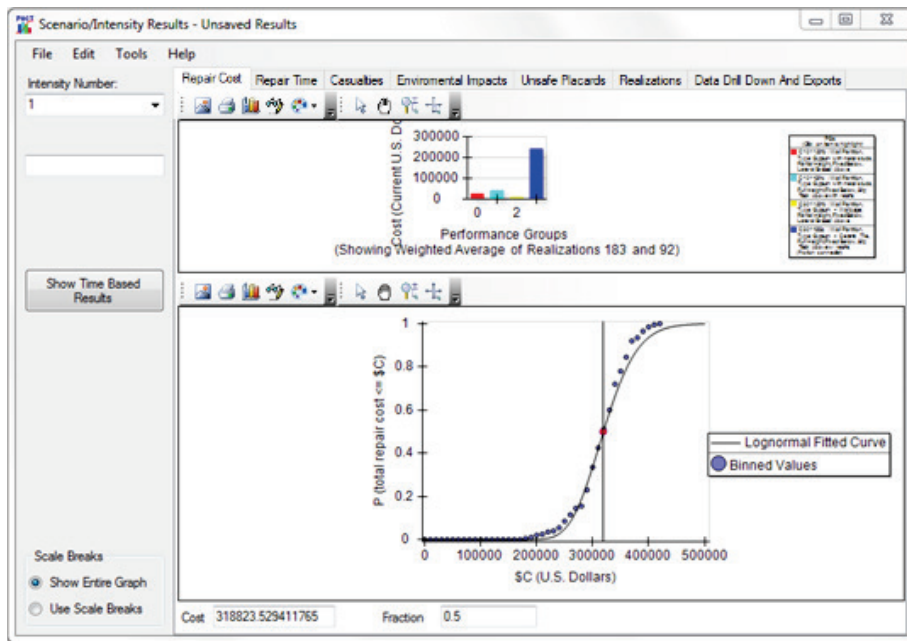


Figure C-22 Results window.

C.7.1 Scenario/Intensity Results

By default, PACT initially displays the **Scenario/Intensity Results** window, shown in Figure C-22.

In all of the tabs in this window, by default, the cursor moves along the data bins and not the lognormal curve. This can be changed using the *Options* menu, as shown in Figure C-23.

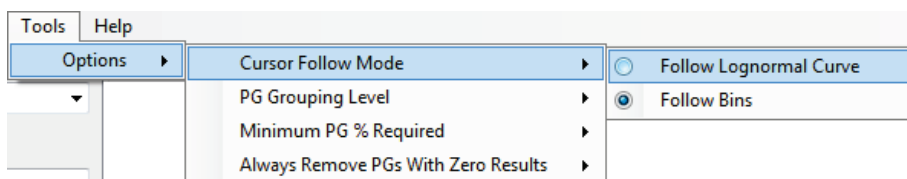


Figure C-23 Performance curve display options.

Clicking the legend of a performance group on the bar chart causes the bar chart for that performance group to stand out by darkening the color of other bars. A click on the top of the legend box restores the original colors. The radio buttons provided at the bottom left of the form can be used to either show the entire graph or use scale breaks for viewing details at either end of the horizontal scale, as shown in Figure C-24.

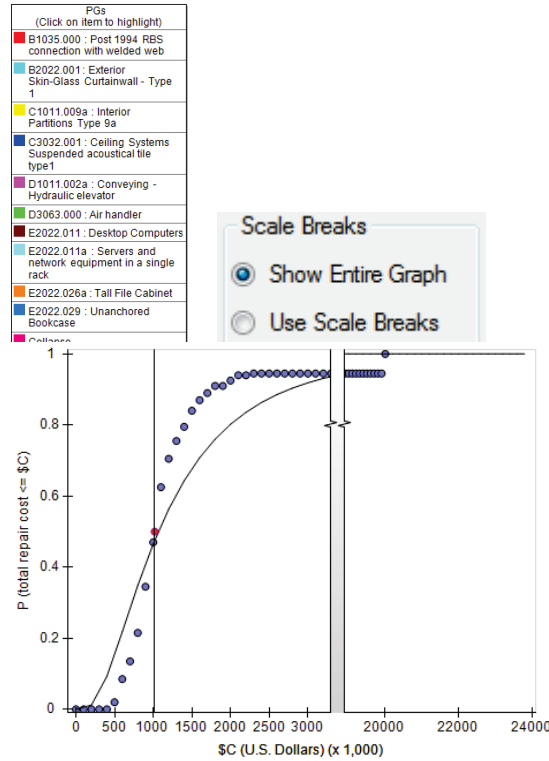


Figure C-24 Results displays.

For any of the graphs, fragilities can be grouped by their Uniformat ID, which will simplify the keys on the graphs. Under the *Tools/Options* menu there is an entry titled *PG Grouping Level*, as shown in Figure C-25. The categories range from *All Fragilities* where each fragility will be one entry in the graphs with own key entry and color, all the way to *Group by Uniformat Major Group Elements*, where all the fragilities will be grouped into top level categories such as “shell,” “interior,” and “equipment and furnishings.” This will be particularly helpful with buildings containing many fragilities. Figure C-26 illustrates the effects of changing the performance grouping levels.

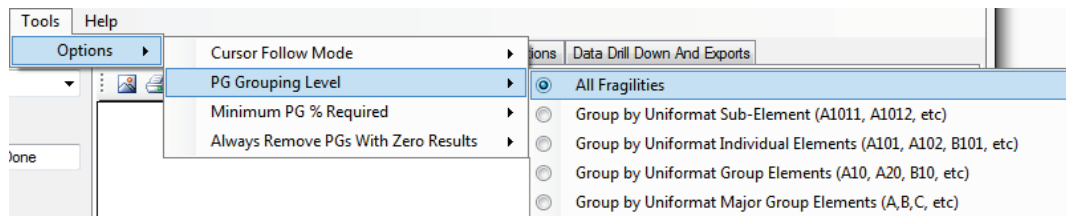
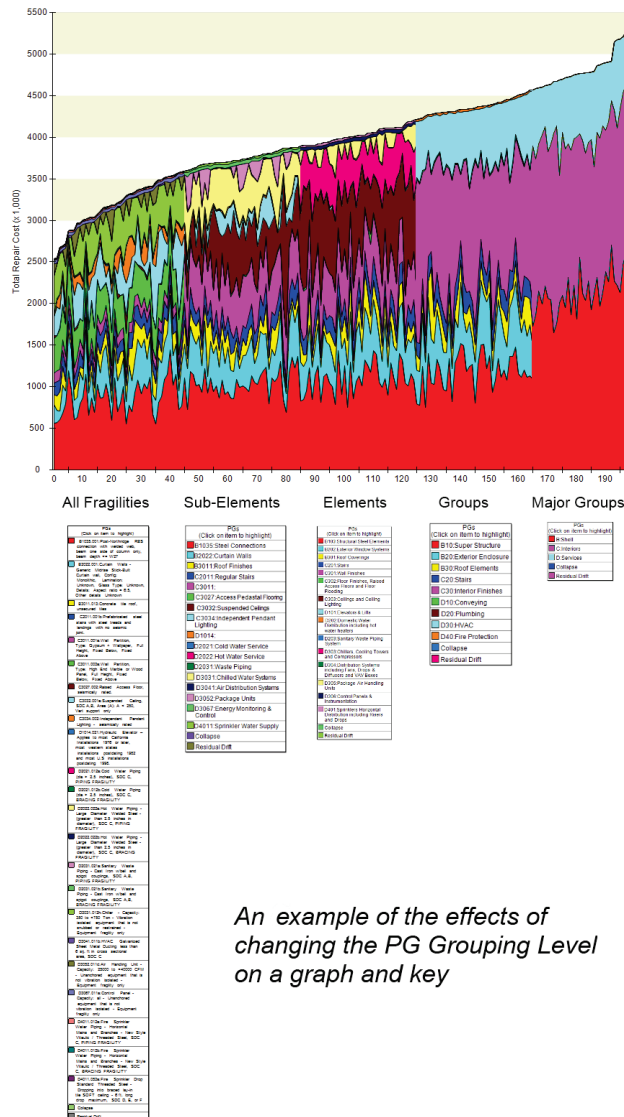


Figure C-25 Changing performance grouping levels.



An example of the effects of changing the PG Grouping Level on a graph and key

Figure C-26 Effects of changing performance grouping levels.

C.7.1.1 Repair Cost Tab

The **Repair Cost** tab, shown in Figure C-27, contains two graphs. By placing the cursor at the line separating the two graphs and holding the mouse key down, and the line can be dragged to make either graph smaller or larger. The desired Scenario/Intensity number can be selected using the drop down list at the top left of the form.

The graph at the bottom of the form depicts the loss curve for cost associated with the selected scenario/intensity for all performance groups in all directions and throughout the height of the building. By default the cursor on the graph is placed at the median value. However, clicking anywhere on the curve will allow examining losses at various probabilities.

Note that the values corresponding to the selected point on the curve are displayed on the text boxes at the bottom of the form. Instead of clicking the cursor on the curve, a cost or probability can be entered in the text box and the corresponding value will be shown in the other text box and the cursor will move to the corresponding location on the curve.

The bar chart on the top depicts the distribution of losses among various performance groups. Note that when the cost or probability on the loss curves is changed the distribution of costs among performance groups shown on the bar chart changes.

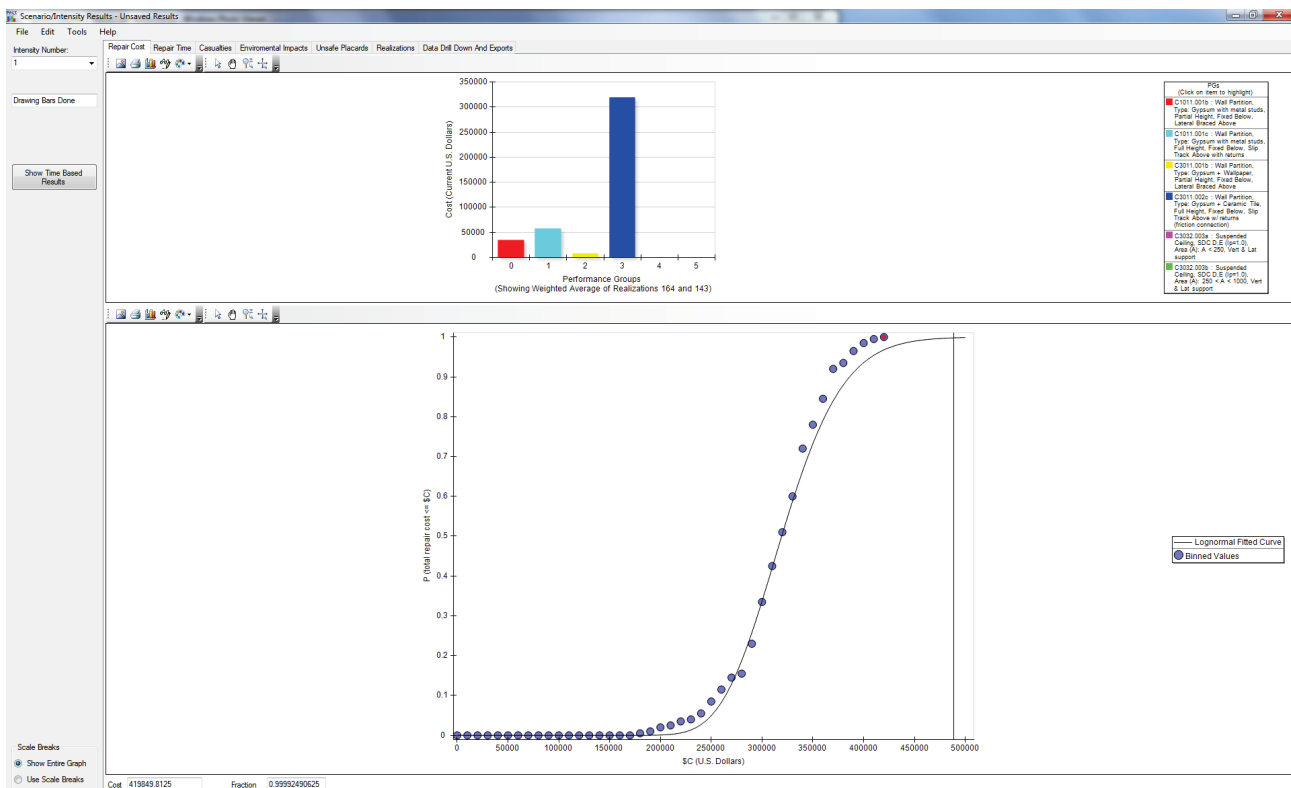


Figure C-27 Repair Cost tab.

C.7.1.2 Casualties Tab

The **Casualties** tab, shown in Figure C-28, contains four graphs. By placing the cursor at the lines separating the graphs and holding the mouse key down, and the lines can be dragged to resize the graphs. The desired scenario/intensity number can be selected using the drop down list at the top left of the form.

The graphs at the bottom of the form depict casualty probabilities associated with the selected scenario/intensity. By default, the cursor on the graph is placed at the median value. However, clicking anywhere on the curve will allow examining losses at various probabilities.

Note that the values corresponding to the selected point on the curve are displayed on the text boxes at the bottom of the form. Instead of clicking the cursor on the curve, a cost or probability can be entered in the text box and the corresponding value will be shown in the other text box and the cursor will move to the corresponding location on the curve.

The bar chart on the top depicts the distribution of casualties caused by various performance groups and collapse (if occurring). Note that when the cursor position is changed, the distribution of casualties per performance groups shown on the corresponding bar chart changes.

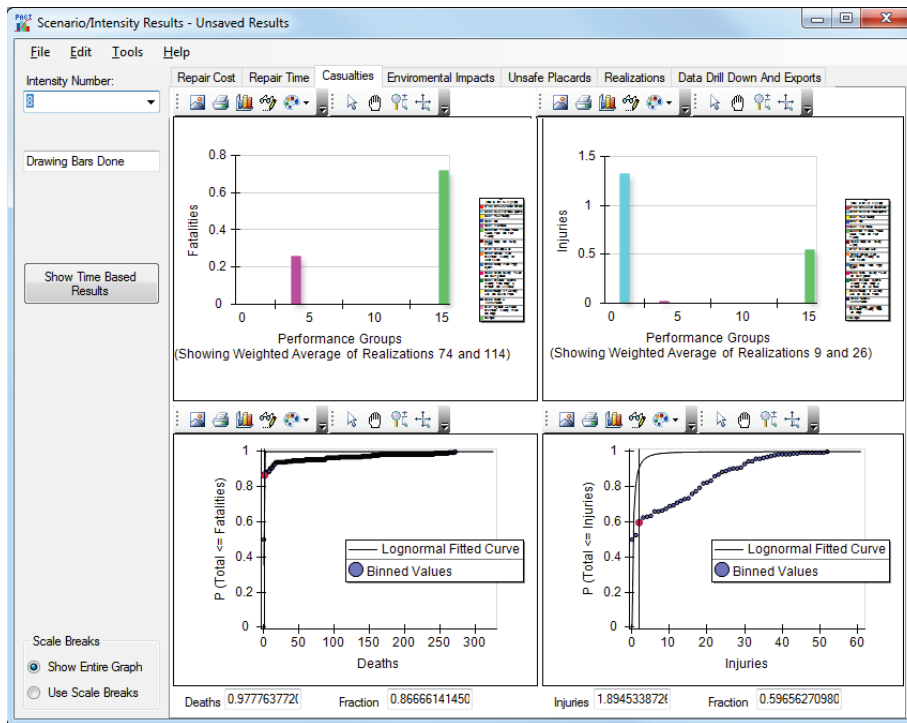


Figure C-28 Casualties tab.

C.7.1.3 Repair Time Tab

PACT estimates repair time by considering two repair strategies:

1. Serial time in which repair activities are limited to one floor at a time, and
2. Parallel time in which all floors will be subjected to repair activities at the same time.

Repair strategy can be selected by clicking the desired radio button, as shown in Figure C-29. Also note that PACT identifies and reports items that may require a long lead time just below these radio buttons.

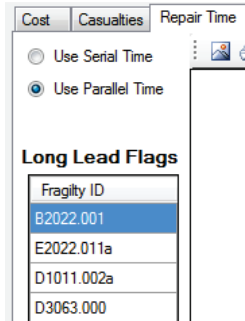


Figure C-29 Repair strategy selection menu.

For realizations that result in structural collapse, the program equates the repair time to the user supplied total replacement time for the building.

In Figure C-30 and Figure C-31, the bottom graph shows the repair time probability and the top chart shows the total repair time and contribution of each performance group to the total repair time.

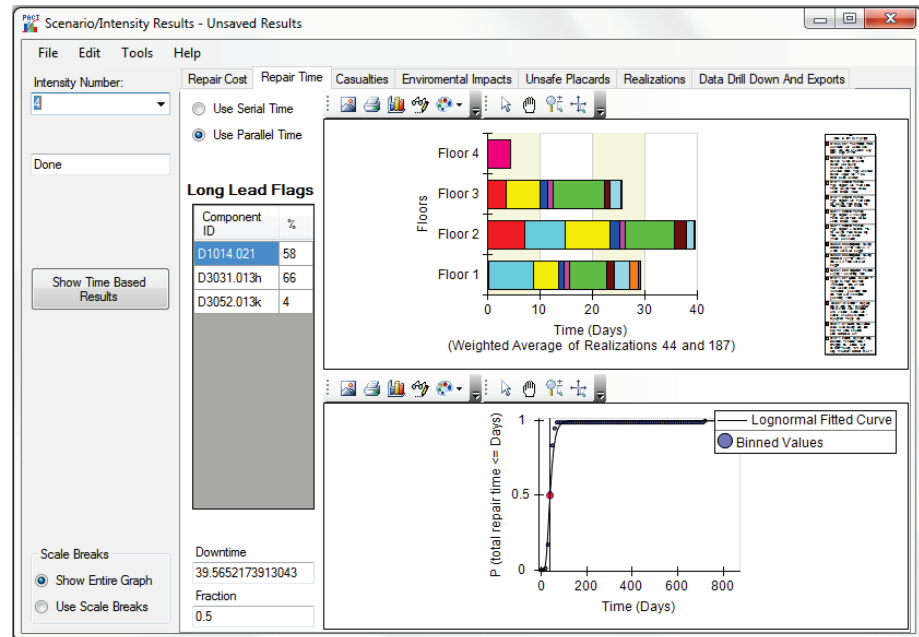


Figure C-30 Repair time output assuming floors are repaired in parallel.

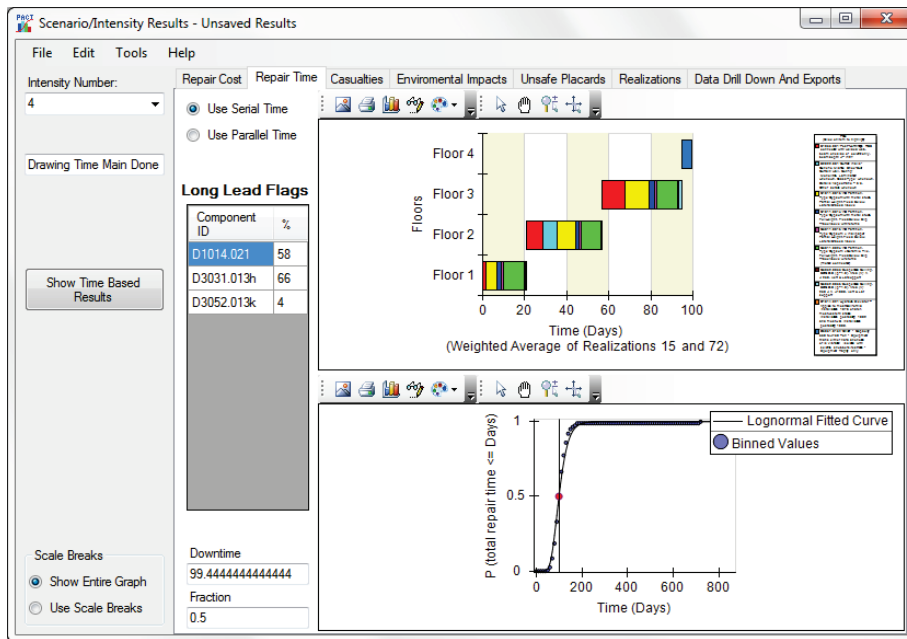


Figure C-31 Repair time output assuming floors are repaired sequentially.

C.7.1.4 Environmental Impacts

For each scenario/intensity, the probability of various environmental impacts for the building is displayed, as shown in Figure C-32. The desired scenario/intensity number can be selected using the drop down list at the top left of the form.

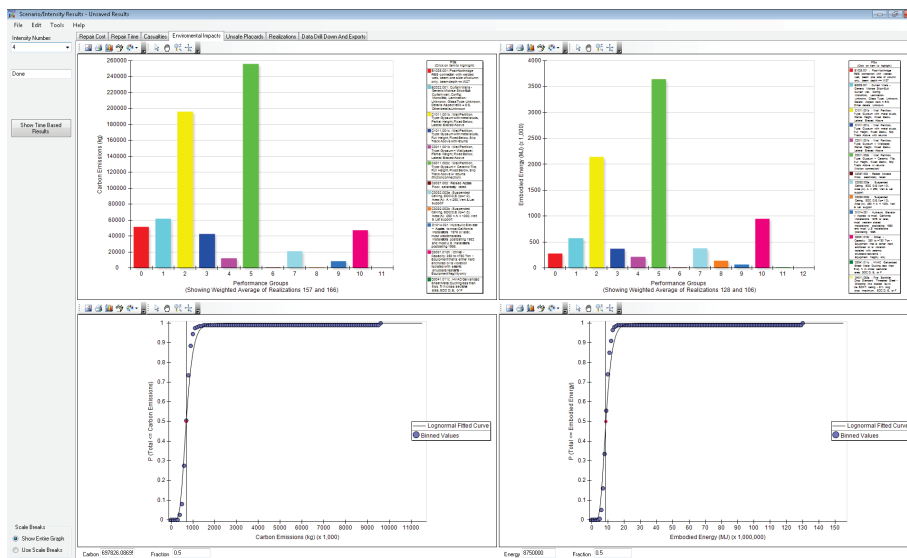


Figure C-32 Environmental Impacts tab.

C.7.1.5 Unsafe Placards Tab

For each scenario/intensity, the probability of various performance groups triggering an unsafe placard for the building is displayed, as shown in Figure

C-33. The desired scenario/intensity number can be selected using the drop down list at the top left of the form.

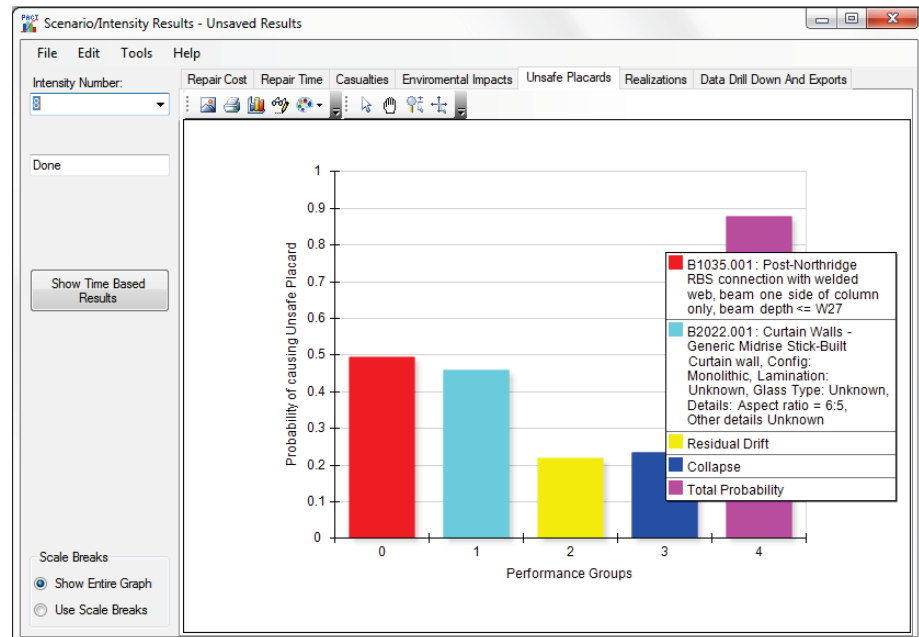


Figure C-33 Unsafe Placards tab.

C.7.1.6 Realizations Tab

The **Realizations** tab provides a graphical snapshot of results of each realization performed by the program. As shown in Figure C-34, there are four categories to choose from: (1) repair cost; (2) repair time; (3) number of fatalities; and (4) number of injuries.

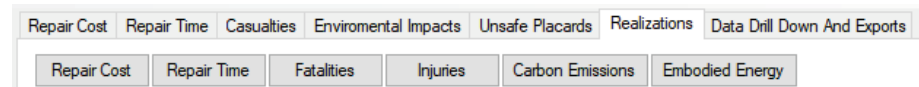


Figure C-34 Realizations categories.

PACT displays the consequences reported by each realization and the breakdown of each consequence into contributing performance groups. The realizations are ordered in the ascending order of the consequence, not the number assigned to the realization. For example, Figure C-35 shows the total cost and repair time reported by realizations. Note that only about 15 of the 200 realizations resulted in structural collapse, another 15 had irreparable residual drift. There is a big difference in cost between those 30 realizations and those that just had component damage. The total replacement time is reported in Figure C-35 for realizations reporting structural collapse or irreparable residual drift.

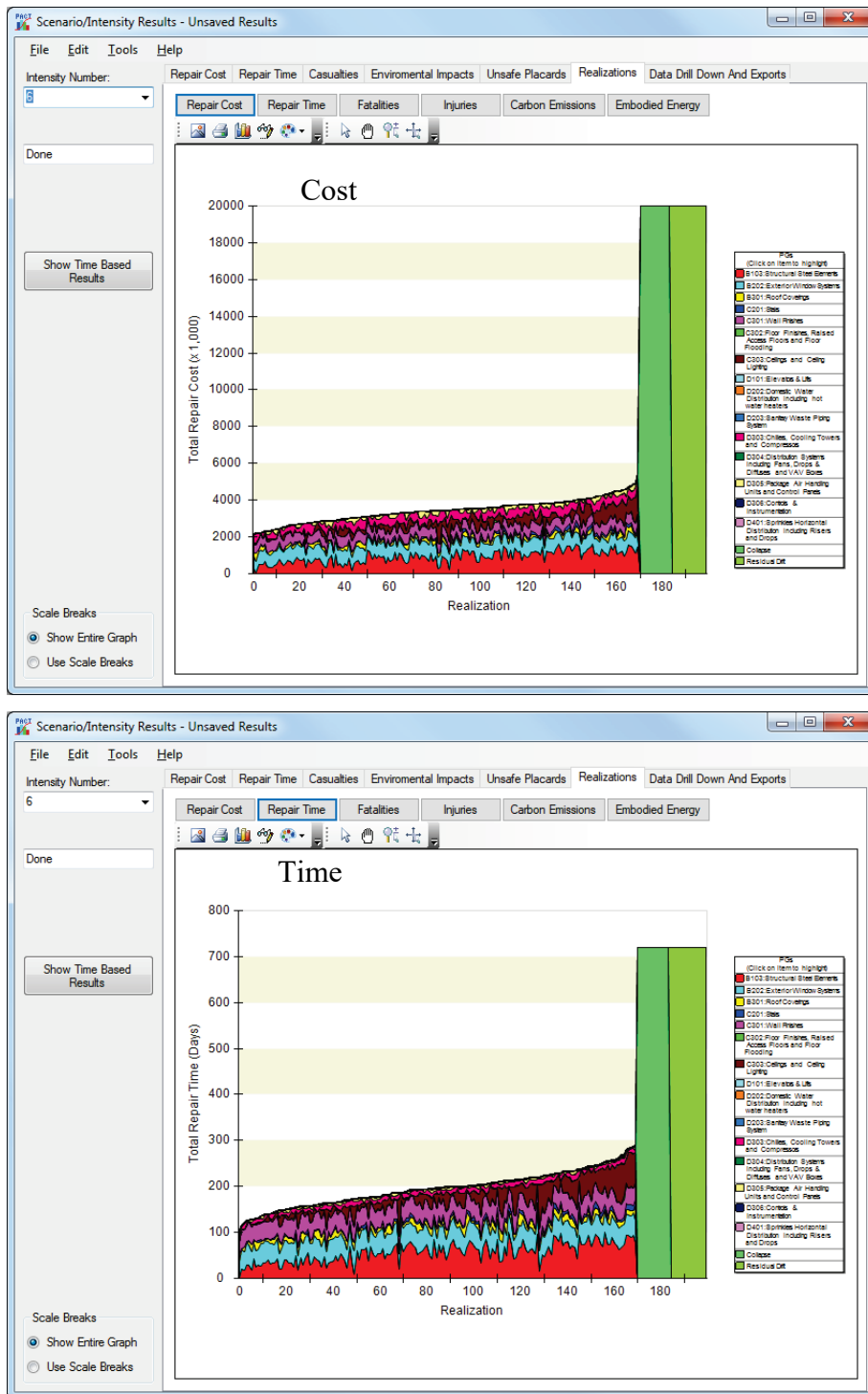


Figure C-35 Individual Realization display of repair cost (top) and repair time (bottom) contributions by performance group.

C.7.1.7 Data Drill Down and Exports Tab

This **Data Drill Down And Export Tab** allows for examination or export of results from a single realization or export of results of all realizations in a

comma separated value (CSV) format compatible with Microsoft Excel and most other spreadsheet programs.

To examine results obtained from individual realizations, clicking [View Drilldown page](#) will display the **Results Drill Down** window. On this window a particular intensity or scenario, a realization, a particular floor and direction, a performance group, and even a particular item within the performance group can be examined for more information.

The table on the top of the window shown in Figure C-36 provides a summary for Intensity/Scenario #1, Realization #1, Direction 1, and Performance Group B1035.001. Clicking [Show More Information](#) will allow even deeper examination.

Result Drill Down

Intensity/Scenario: 1

Realization: 1

Floor: 1

Direction: Direction 1

Performance Group: 1: B1044.102a

Item Number: 1

Damage State:

	Minimum	Average	Maximum
Repair Cost	\$0.00 (Real #1)	\$19,855.96	\$644,276.71 (Real #7...
Repair Time	0 (Real #1)	1.361	59.891 (Real #731)
Injuries	0 (Real #1)	0	0.008 (Real #849)
Fatalities	0 (Real #1)	0	0.003 (Real #765)
Carbon Emissio...	0.00 (Real #1)	5,656.87	227,089.54 (Real #731)
Embodied Ener...	0.00 (Real #1)	71,757.92	2,735,834.82 (Real #...

Realization 1

Date And Time: May 30 11:51:02 P

SA(T) final: 0.300

Total Population: 47.6

Floor 1

Total Population: 9.5

Direction 1

Performance Group 1

Fragility: B1044.102a

Slender Concrete Wall, 18" thick, 12' high, 20' long

Population Group: None

Item Number 1

Quantity: 1

Damaged: 0

Demand Value: 0.00018

Damage State -

Embodied Energy: N/A

Carbon Emissions: N/A

Repair Cost/Unit*: \$0.00

Repair Time/Unit**: 0

Fatality Area: 0

Injury Area: 0

Carbon Emissions: 0

of Unsafe Placard Items: 0

Is Long Lead item: No

EDP Group: Effective Drift

Carbon Emissions: 0

Has Unsafe Placard: N/A

Is Long Lead: N/A

* Costs not adjusted for Date or Location.

**Times are "Person Days" and not adjusted for Maximum workers per area.

[Show More Information](#)

[Exit](#)

Figure C-36 Result Drill Down screen.

There are two choices for exporting the results of realizations. High-level exports produce files containing more significant information while low-level exports contain every bit and piece of the information generated by the program. The available options are shown in Figure C-37.

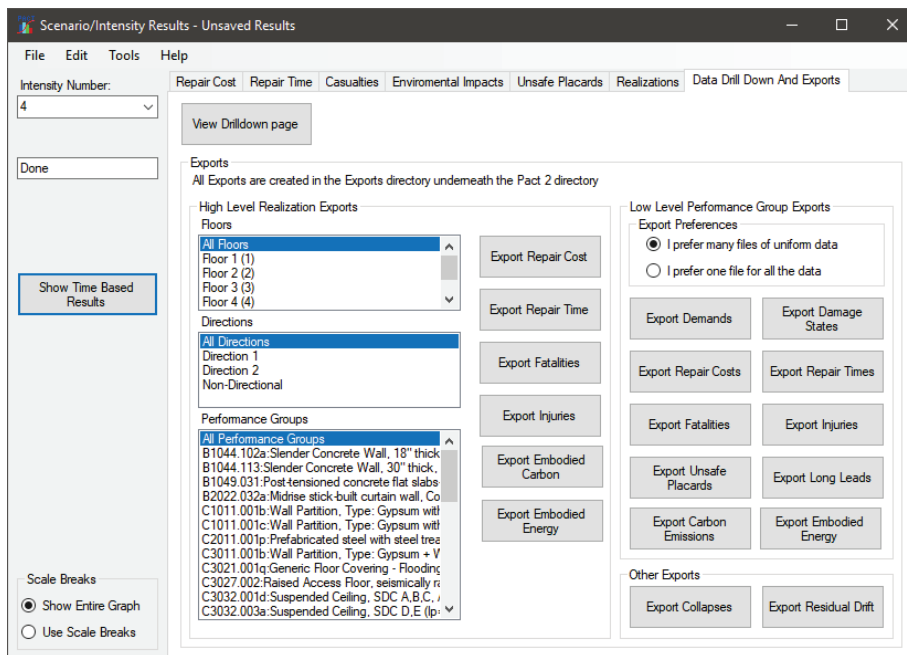
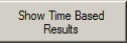


Figure C-37 Screen showing options for exporting results.

C.7.2 Time-Based Results

Selecting the  button on the Scenario/Intensity Results window shown in Figure C-22, will initiate the time-based results window, shown in Figure C-38. This window has two tabs that show time based results and loss area charts. The time based results tab is split into 6 sub tabs that show annualized total values for repair cost, repair time, fatalities, injuries, carbon emissions, and embodied energy. The shaded colors in each graph represent the contribution of various intensities to the total annual loss.

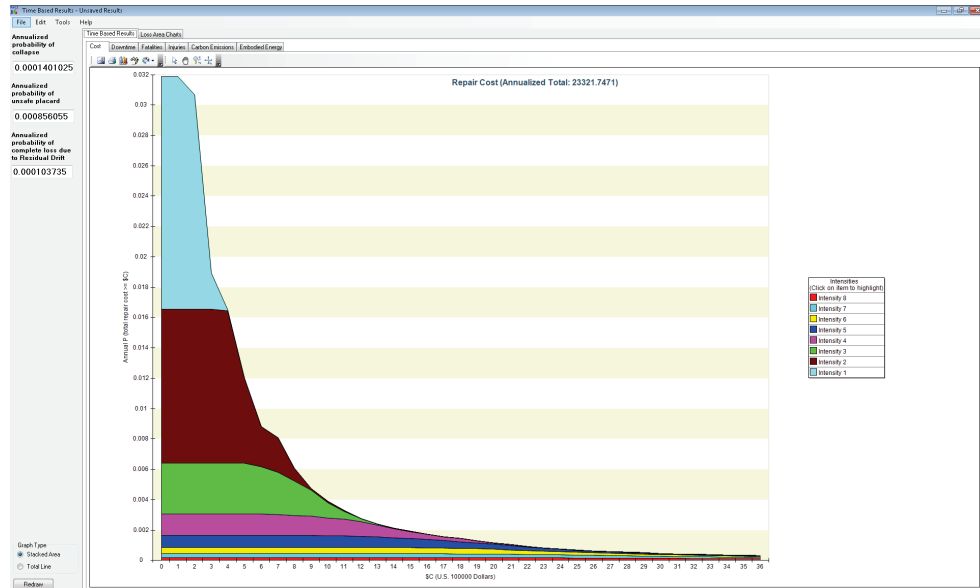


Figure C-38 Time-based results output screen.

Clicking on the legend of any of the charts causes the chart to highlight the selected data by darkening the color of other data. A click on the top of the legend box restores the original colors.

By default, the annualized total and graphs are the integration of the data bins from each analysis. In order to view annualized totals integrated using the lognormal fitted curves, the option can be selected as shown in Figure C-39.

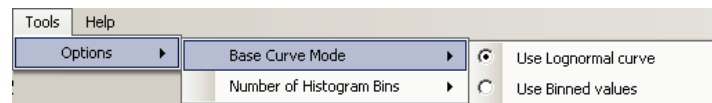


Figure C-39 Options menu showing base curve mode selection.

When integrating using the data bins, the number of data bins can have an effect on the totals and the graphs. The number of bins used can be adjusted in the *Options* menu, as shown in Figure C-40. The number of bins actually used will depend on the exact data being evaluated, but it will never be larger than the number specified by the user.

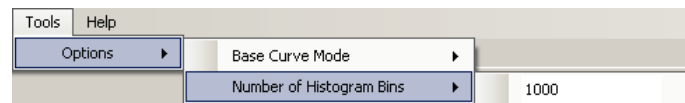


Figure C-40 Options menu showing histogram bins option.

The graph type (either color coded by the contribution of each intensity, or as a single curve showing the total amount) can be changed with the radio buttons on the bottom left of the form.

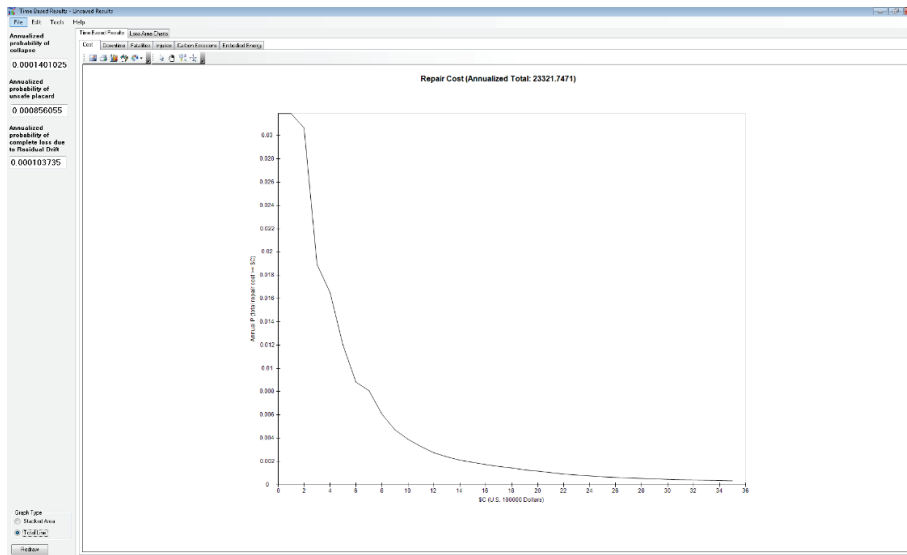


Figure C-41 Average annualized loss output screen.

On the left side of the form the annualized probabilities of structural collapse and unsafe placard are displayed.

Loss Area Charts tab provides a three-dimensional representation of the charts in their unadjusted form or as adjusted by application of mean annual frequency of exceedance values. Figure C-42 shows the different options available for display.



Figure C-42 Loss area charts buttons.

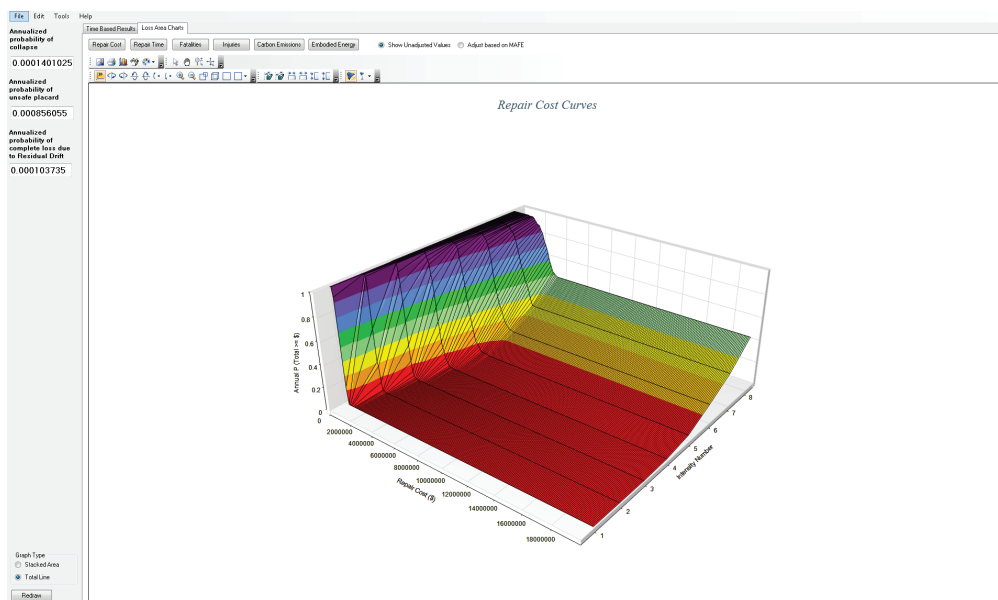


Figure C-43 Loss Area Charts tab.

C.8 Fragility Specification Manager

Attention is needed when experimenting with fragility functions definitions, because any changes made here can radically change the outcome of the loss analysis. It is recommended that a backup of the “\ATCCurves” folder originally provided with PACT be made before making any changes to the fragility functions.

The **Fragility Specification Manager** utility allows editing of fragilities and creation of new fragility specifications.

The *File* menu provides the option to create a new fragility specification from scratch, save a fragility specification. This menu is shown in Figure C-44. In the *Edit* menu, an option to duplicate an existing fragility specification is given. The duplicate fragility would be used as the basis for a new fragility. The *Tools* menu provides the ability to switch default measurement system between imperial and metric units.

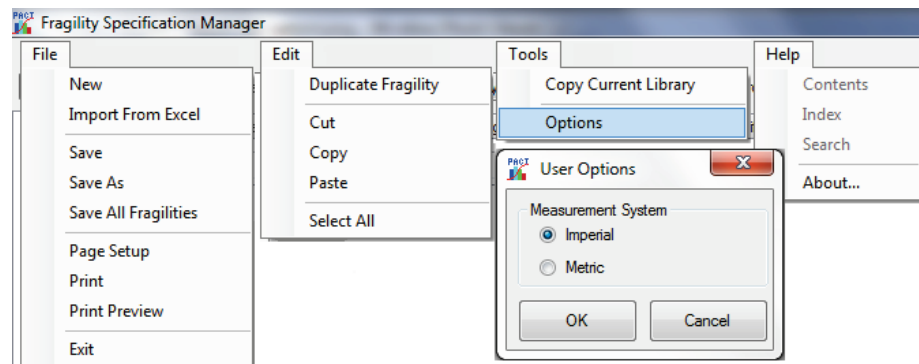




Figure C-44 File, Edit, and Tools menus.

C.8.1 Overview Tab

The **Overview** tab, shown in Figure C-45 provides a list of all the fragility specification categories in a tree structure, along with all the existing fragilities. Any category that has one or more fragilities underneath it will be marked as bold. Any subcategory can be expanded by clicking the small  symbol, or hidden by clicking the  symbol.

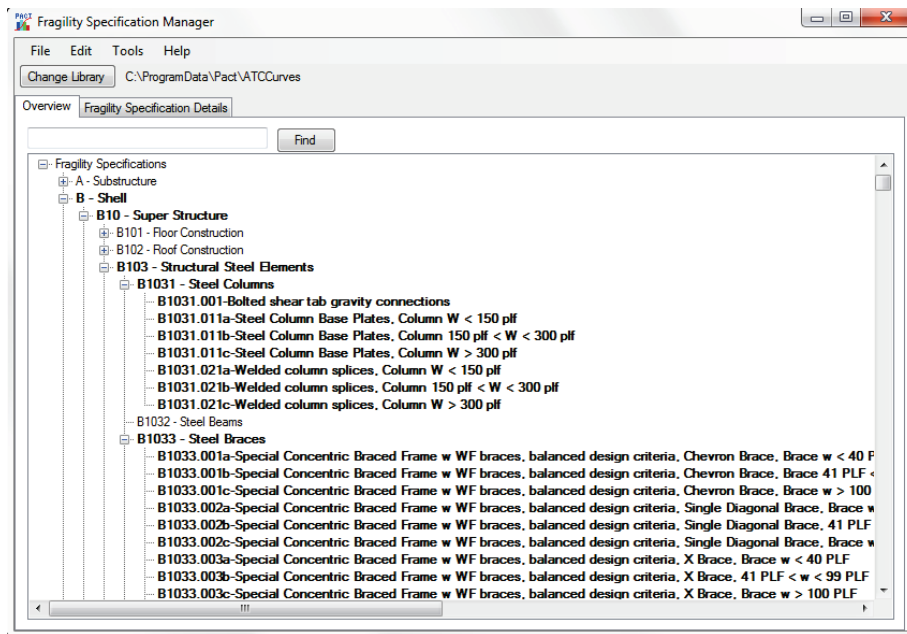


Figure C-45 Overview tab.




The search box on the top can be used for searching all the existing fragilities for an ID or description containing that text.

The fragilities are organized with the following:

- Top Level Category:
 - A – Substructure
 - B – Shell
 - C – Interiors
 - D – Services
 - E – Equipment & Furnishings
 - F – Special Construction
- 2nd Level Category:
 - Top level followed by 2 numbers from 10 to 99, e.g., A10
- 3rd Level Category:
 - 2nd Level followed by one number 1-9, e.g., A101
- 4th Level Category:
 - 3rd Level followed by one number 1-9, e.g., A1011

In addition, a specific fragility classification number would include all four levels and an optional letter, e.g., A1011.000 or A1011.555v.

C.8.2 Fragility Specification Details Tab

At the top of the **Fragility Specification Details** tab, shown in Figure C-46, is a navigation bar, which lists the fragility specification being examined. It also allows for navigation through all of the existing fragilities using the arrows. It also provides buttons to add a new fragility , and delete an existing fragility , and save an existing fragility .

Below the navigation bar, the information on the current fragility, divided between a tree view on the left showing the basic structure of the fragility and its damage states and consequences, and detail information on the right, is displayed. The border between the tree view and the detail information can be moved left or right by clicking and dragging on the border between them.

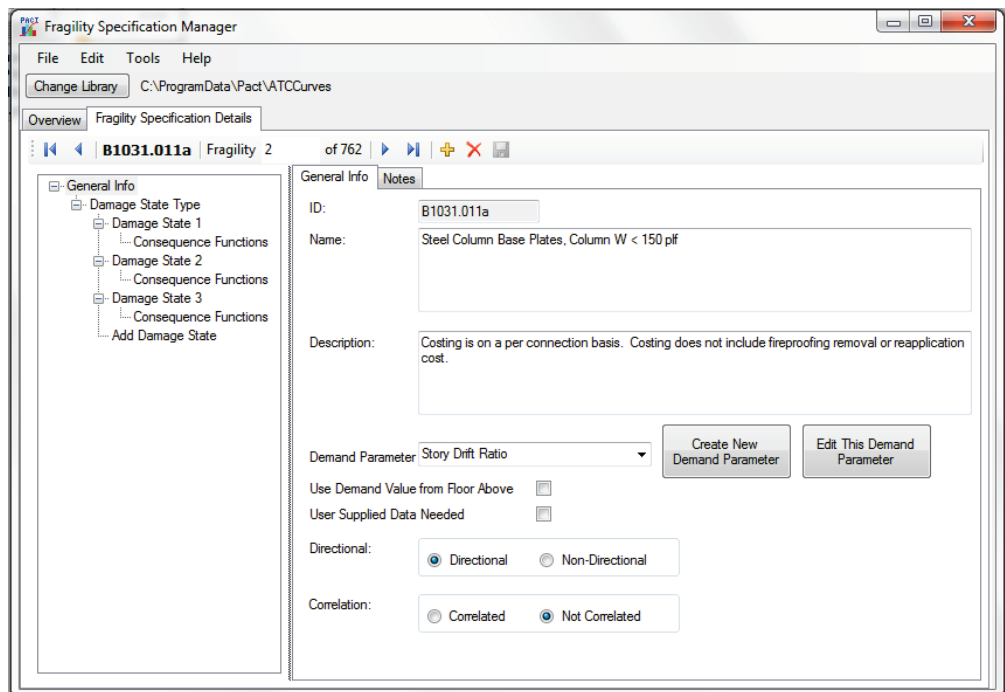


Figure C-46 Fragility Specification Details tab.

When a new fragility is added or an existing one is duplicated, the Uniformat ID number will be requested. The format of the ID field that the fragility manager expects is a single upper case letter between A-F followed by two digits from 10 to 99, two more digits from 11 to 99, followed by a period, then 3 more digits from 000 to 999, followed by an optional lower case letter from a to z.

C.8.2.1 Fragility Structure Tree View

The fragility structure consists of general information for the fragility and various damage state groups and sub-damage state groups, individual damage states, and consequences.

The easiest structure is that of a sequential fragility. It consists of general information, a single damage state group (designated with the title of “Damage State Type”), one or more individual damage states, and consequences for each of those damage states.

The structure of a mutually exclusive or simultaneous fragility is more complicated. In either case, a “master” sequential damage state group (designated with the title of “Damage State Type”) with only a single damage state is provided. This damage state is used to determine if the item in question is damaged at all based on the value of the demand parameter of a particular realization. If it is determined that there is some damage, the sub-damage state group is marked as either simultaneous or mutually exclusive, with two or more damage states to determine the exact kind of damage, with consequence functions for each damage state. Both types of fragilities are illustrated in Figure C-47.

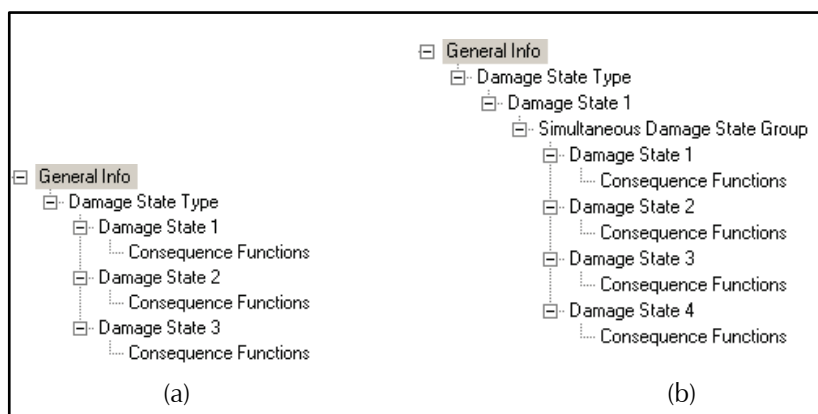


Figure C-47 Tree view showing: (a) sequential; and (b) simultaneous fragilities.

PACT does not limit the user to these options. It is possible to have multiple damage state groups of all different types nested underneath each other, but the utility of these options is limited. Two examples are shown in Figure C-48.

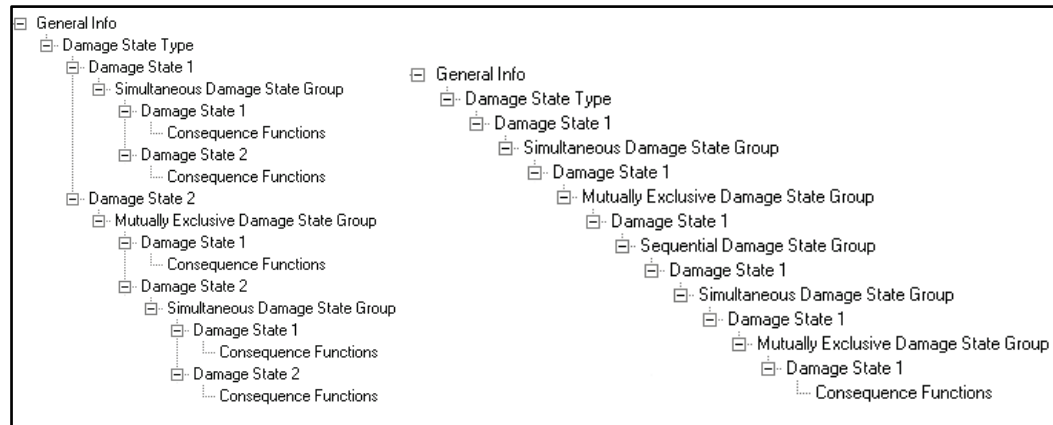


Figure C-48 Example complicated fragility structures consisting of multiple sub-damage state groups and sub-sub-damage state groups of several different types.


A new fragility can be created by clicking  or using the *File* menu. The tree structure will look as shown in Figure C-49.



Figure C-49 Basic damage state level.

The program provides general info and a master damage state by default. When **Add Damage State** is clicked it will add Damage State 1.

If a simple sequential fragility function is being created, more damage states can be added by clicking on **Add Damage State**. Clicking on **Consequence Functions** for each damage state will allow adding of consequence information, as shown in Figure C-50.

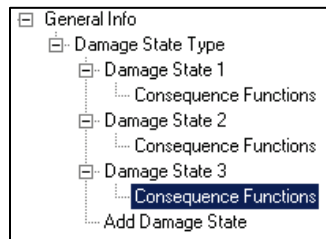



Figure C-50 Consequence functions.

Any damage state, consequence, or damage state group (except the very top level one), can be deleted by right clicking on the item and choosing **Delete** or selecting it and hitting .

In order to create a mutually exclusive or simultaneous fragility, first the top-level damage state needs to be created, then a damage state group can be added. In Figure C-51, note that there are two places that say **Add Damage State**. The first is connected by a line to the master damage state group, and is the same level as Damage State 1. That one will add a Damage State 2 to

the master group. The second one is under the level of the “Sequential Damage State Group,” and will add a damage state to this subgroup. When this damage state is selected, the selection in the combobox shown in Figure C-52 can be changed to Mutually Exclusive or Simultaneous. Selecting “Add Damage State” that is right under the Sequential Damage State Group text changes the text to say “Mutually Exclusive Damage State Group,” with an option to add the first damage state to it. This is shown in Figure C-53.

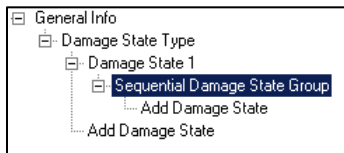


Figure C-51 Adding damage state to different groups.

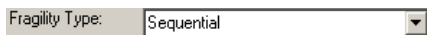


Figure C-52 Combobox for selecting fragility type.

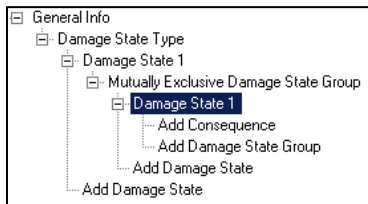


Figure C-53 Creating mutually exclusive damage states.

C.8.2.2 General Info Tab

When **General Info** is selected on the tree view, the screen shown in Figure C-54, separated into two tabs on the right, is displayed. The **General Info** tab will show the most important general information about the fragility.

The Fragility ID is shown, but is not editable, along with the short name and a longer description of the fragility. The demand parameter can be selected from a dropdown menu, or created new, as shown in Figure C-55. In addition, the fragility can be specified as directional or non-directional, and correlated or not correlated.

Fragilities can be marked as using the demand values of the floor above, by using the checkbox marked **Use Demand Value from Floor Above**. This is used for components such as ceiling tiles or sprinkler pipes, which affect the casualties of the floor they are on, but use the accelerations of the floor above them to determine their damage state.

Some fragilities will require user-entered values, and are therefore incomplete. These fragilities are marked with the checkbox labeled “User Supplied Data Needed.” The user is expected to edit these fragilities for their

specific building, depending on the exact nature of the component. For instance, there are fragilities for computers that have the demand values to determine if the computer is damaged, but not the cost values because that differs based on the specific circumstance. The program will provide a warning if these fragilities are being used without entering in the required values.

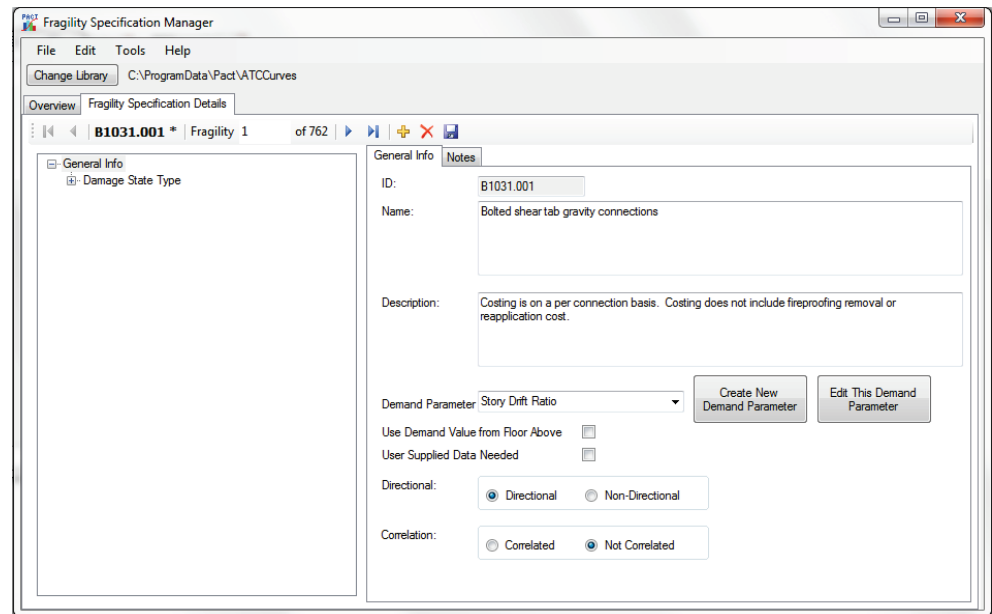


Figure C-54 General Info tab on Fragility Specification Details screen.

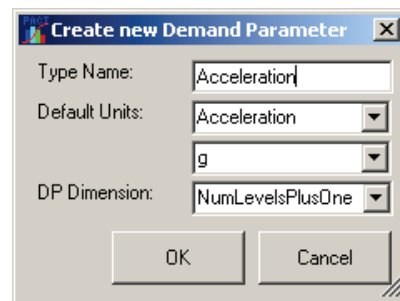


Figure C-55 Create New Demand Parameter window.

C.8.2.3 Notes Tab

The **Notes** tab is shown in Figure C-56 and contains miscellaneous information about the fragility. Included here is the date the fragility was created, whether it is an official and approved fragility, the rating of its quality, the author information, and any other notes.

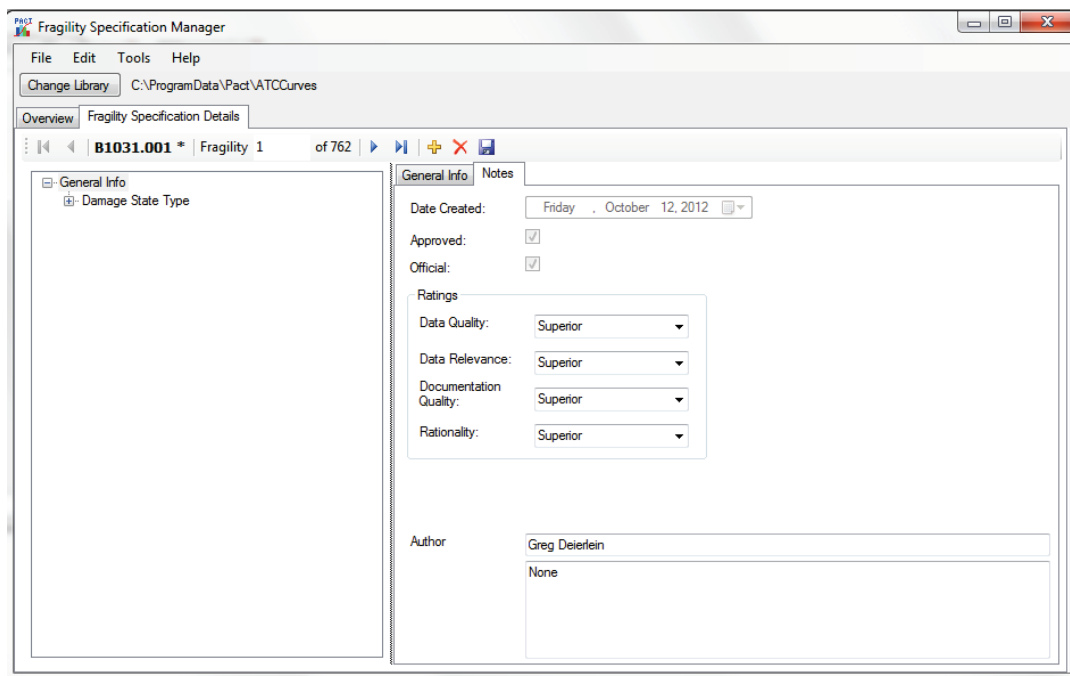


Figure C-56 Notes tab on Fragility Specification Details screen.

C.8.2.4 Damage State Group

When any Damage State Group is selected on the tree view, including the top level group named “Damage State Type,” a screen on the right will be displayed. The information consists of a dropdown list showing the damage state group type (Figure C-57), and a graph of all the damage states in that group. If it is the top level group, the fragility type cannot be changed. If the damage group type is sequential, a line graph showing the probability of each damage state against the possible demand parameter values will be shown (see Figure C-58).

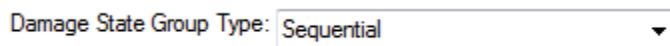


Figure C-57 Damage State Group Type dropdown menu.

If the damage state group type is simultaneous, a bar graph with the probabilities of its damage states will be displayed, as shown in Figure C-59a. If the damage state group type is mutually exclusive, a pie chart with the probabilities of its damage states will be displayed, as shown in Figure C-59b.

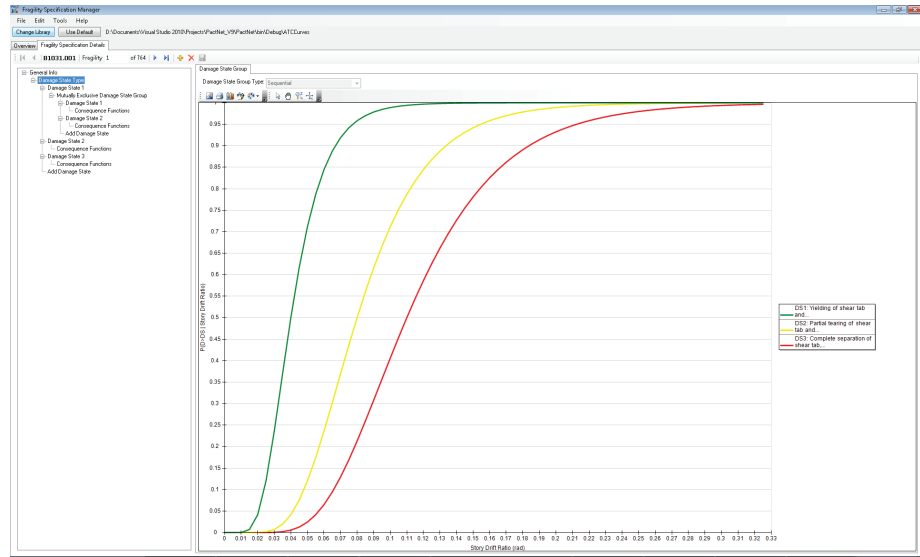
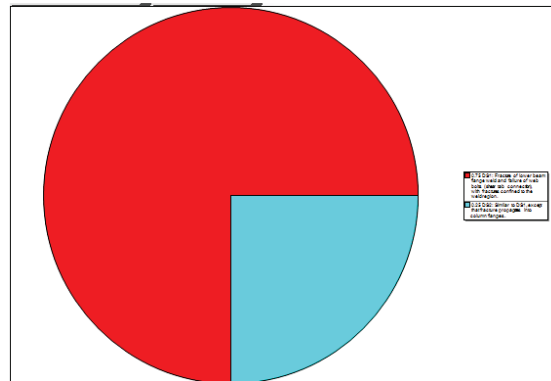
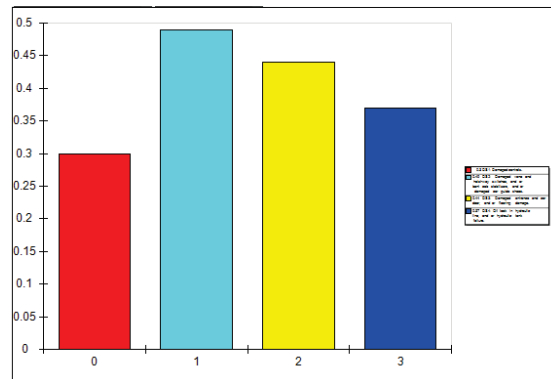


Figure C-58 Damage State Group screen.



(a)



(b)

Figure C-59 Fragility data display showing:
(a) simultaneous damage state group; and (b) mutually exclusive damage state group.

C.8.2.5 Damage State

When any of the damage states on the tree view are clicked, a screen with information about that damage state will be displayed, as shown in Figure C-60. This screen provides a description, an image if one has been specified, and buttons to allow for deletion or addition of an image. If the selection is sequential (or a master damage state group), the median and dispersion values are displayed. If the selection is simultaneous or mutually exclusive the fraction of the time it is in this damage state is displayed.

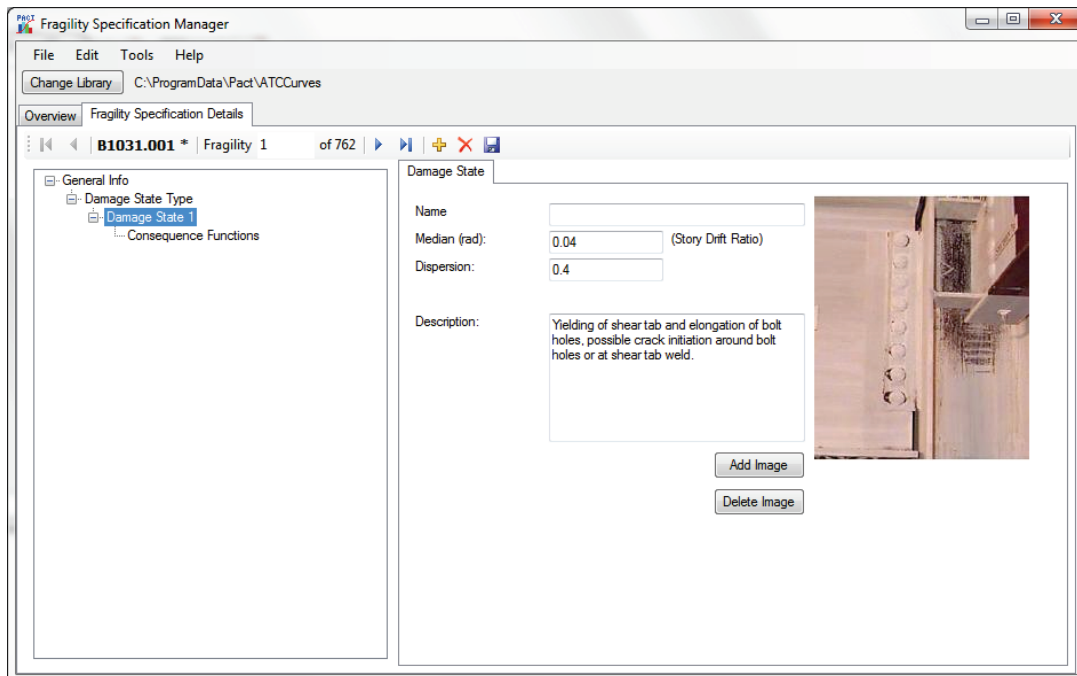


Figure C-60 Damage state information screen.

C.8.2.6 Consequence Functions

When any consequence function on the tree view is clicked, a screen with different consequence information, separated into four tabs, is displayed, as shown in Figure C-61.

In the **General Consequence Info** tab, a description of the repair measures for this damage state is provided.

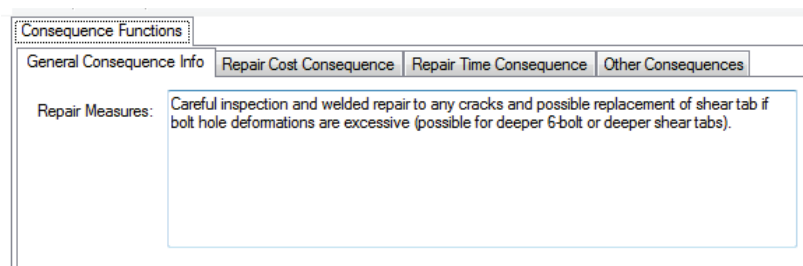


Figure C-61 Consequence Functions screen.

In the **Repair Cost Consequence** tab, shown in Figure C-62, information for costs and cost discounts for this damage state are listed. The lowest quantity at which cost discounts occur and the average cost per unit to repair at that quantity or lower, and the quantity above which there will no longer be cost discounts, and the average cost to repair per unit at that cost or higher should be entered. The cost uncertainty type can also be entered, and depending on if normal or lognormal distribution is chosen, and the dispersion or COV value associated with the uncertainty.

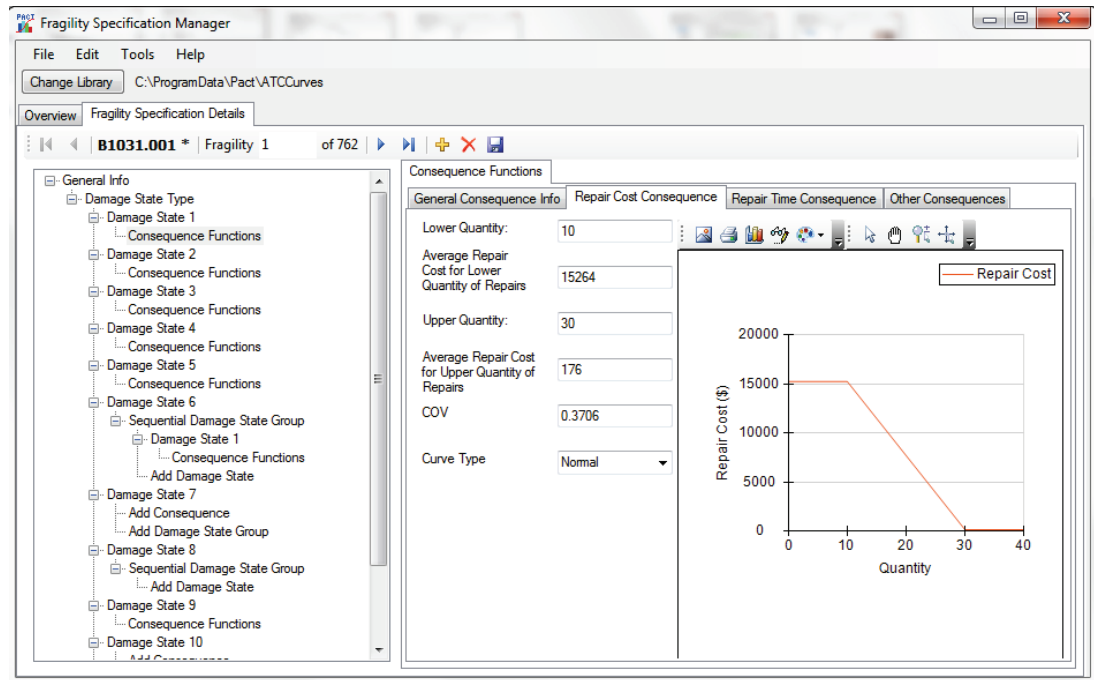


Figure C-62 Repair Cost Consequence tab.

In the **Repair Time Consequence** tab, shown in Figure C-63, the information for time and time discounts for this damage state are entered.

In the **Other Consequences** tab, shown in Figure C-64, information on the unsafe placard consequences, non-collapse casualty consequences, long lead time flags, and environmental losses are provided.

In this tab, use of unsafe placard consequences can also be specified. If not, the fraction of the total quantities required to trigger a unsafe placard need to be entered. PACT will count all the items of this type in the building, and count how many of those items are in this damage state. If the ratio is higher than the median value entered here (adjusted by the dispersion) for a particular realization, it will be marked as getting an unsafe placard. It will not add different damage states together, even different damage states for the same fragility.

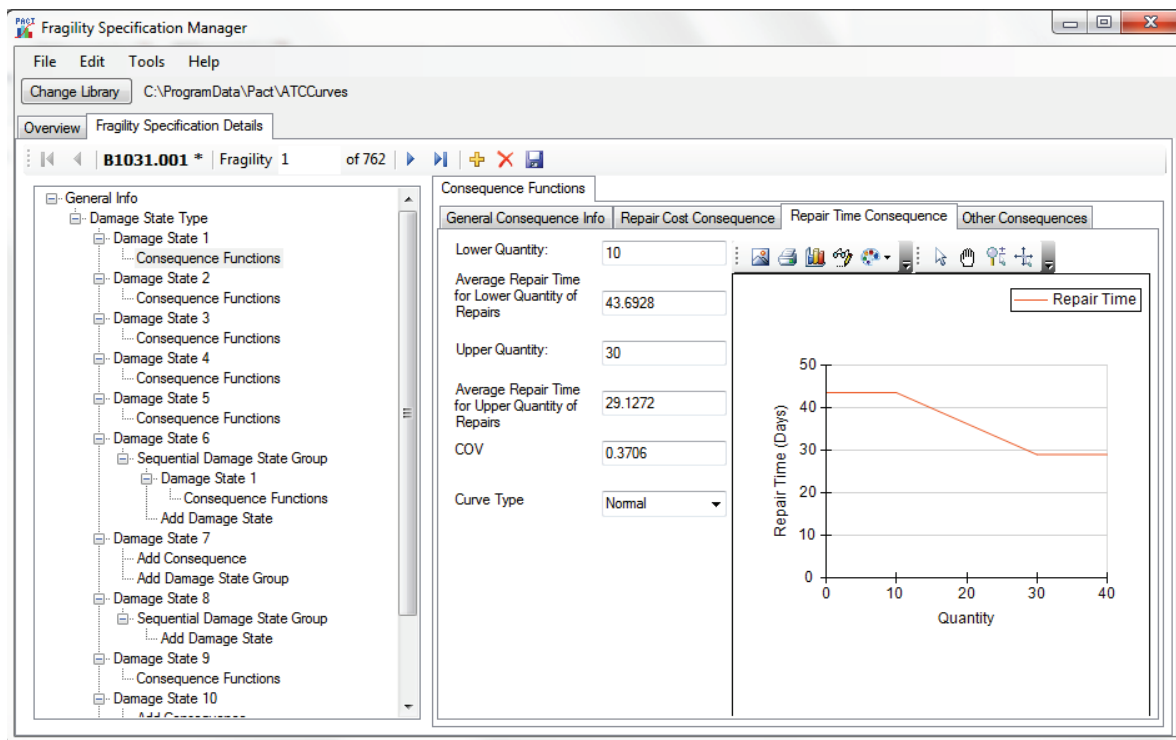


Figure C-63 Repair Time Consequence tab.

The screenshot shows the 'Other Consequences' tab in the 'Fragility Specification Manager'. The tab contains several sections with input fields and checkboxes. The 'Unsafe Placard Consequences' section has a checkbox for 'Possible Unsafe Placard Consequences' and a 'Fraction of Total Quantities to Trigger Unsafe Placard' section with 'Median' (0) and 'Dispersion' (0) fields. The 'Non-Collapse Casualties' section has a checkbox for 'Potential for Non-Collapse Casualties' and two rows of input fields for 'Fatality Rate in Affected Area' and 'Injury Rate in Affected Area', each with 'Median' (0) and 'Dispersion' (0) fields. The 'Long Lead Time' section has a checkbox for 'Use Long Lead Time Flag'. The 'Environmental Losses' section has two rows of input fields for 'Embodied Energy Median (MJ)' (18017.28) and 'Carbon Emissions Median (kg)' (1225.44), each with 'Dispersion' (0.3082) and 'Curve Type' (Normal) fields.

Figure C-64 Other Consequences tab on Fragility Specification Details screen.

Non-collapse casualties can also be defined here by first entering information on how much each floor is affected by an item in this damage state, then what the fatality and serious injury rate are for anyone in that affected area.

Finally, items with a long lead time flags in this damage state can also be indicated here.

C.9 Population Manager

Attention is needed when experimenting with the population library, because any changes made here can change the outcome of the casualty analysis. It is recommended that a backup of the population library originally provided with PACT be made before making any changes to the occupancy functions.

The **Population Manager** is divided into two separate areas, as shown in Figure C-65. The layout is very similar to the population manager in the building manager, except that changing the values here will change them for all future projects.

Hour	Weekdays	Weekend
12:00 AM	0%	0%
1:00 AM	0%	0%
2:00 AM	0%	0%
3:00 AM	0%	0%
4:00 AM	0%	0%
5:00 AM	0%	0%
6:00 AM	0%	0%
7:00 AM	25%	0%
8:00 AM	50%	5%
9:00 AM	75%	5%
10:00 AM	100%	5%
11:00 AM	100%	5%
12:00 PM	50%	5%
1:00 PM	50%	5%
2:00 PM	100%	5%
3:00 PM	100%	5%
4:00 PM	75%	5%
5:00 PM	50%	5%
6:00 PM	25%	0%
7:00 PM	0%	0%
8:00 PM	0%	0%
9:00 PM	0%	0%
10:00 PM	0%	0%
11:00 PM	0%	0%

Figure C-65 Building Population Manager window.

To create a new population model, *New* can be selected from the *File* menu. Fields are provided for entering the name of the population model, the peak number of occupants per 1000 square feet, and the dispersion, population

distribution per month, day of the week and hour of the day. These may be viewed graphically by clicking on the graph tab (see Figure C-66).

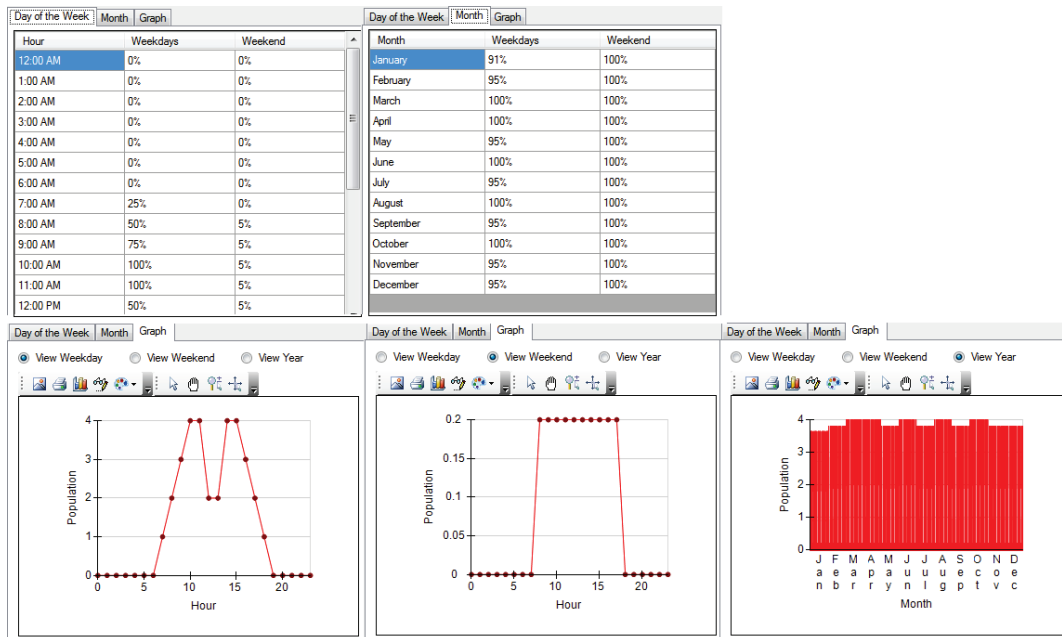


Figure C-66 Population model data screens.

C.10 Reporting

The reporting screen, shown in Figure C-67, will take project or result files, and a Microsoft word template, and create a Microsoft Word report based on them. Two templates are included, one to be used for a Project file (showing the echo of the inputted information) and one to be used for a results file (showing the inputted information and the results).

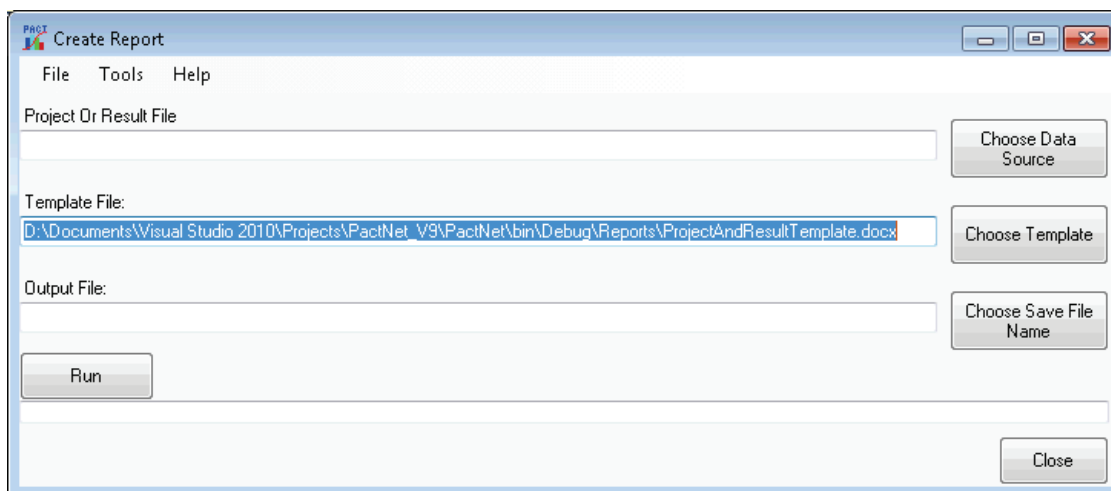


Figure C-67 Create Report window.

The *Tools* menu provides two sets of options for image size: (1) “Size of created images (pixels)” and (2) “Size of images in Word Document (Inches).” The first option is the size that created images (i.e., graphs) will be in the Word document. The default values generally allow for 2 graphs to fit on one page. The second option alters the size of images that are created internally before they are outputted to the Word document, and the size has several effects on the output. As the resolution of the images increases, the graphs get clearer and less blocky, but the fonts do not scale the same way, and so begin to look smaller. It is recommended to use smaller values (200-800) for a report that will most likely be viewed on the computer, and larger values (1000+) when creating reports to print.

Regardless of what values are used for these two options, the aspect ratio (the ratio of width/height) should be the same or very close, or the image will look distorted.

C.11 A Look under the Hood

All data files reside in the Common Application Data folder. For Windows XP, the default location of that folder is “C:\Documents and Settings\All Users\Application Data\Pact,” and for Windows 7 it is “C:\Documents and Settings\All Users\Pact.”

C.11.1 Project Files

All building and project information inputted for a particular project are saved in a single XML file with the project name in the Projects subfolder under the folder where PACT is installed. If the default path was used for installing PACT, the project files may be found in the data folder in “Projects.” Although XML files are text files that can be viewed and changed using any text or word processor, extreme care is necessary if these files are manipulated, as even minor manual changes may render a project file unusable. A copy of the project file can be easily created with no adverse effects.

C.11.2 Results Files

All result information if saved, is saved in a single file with the result name in the Projects subfolder under the folder where PACT is installed. If the default path was used for installing PACT, the project files may be found in data folder at “Projects.” Result files can be saved as binary files, with the file extension .bin or as XML files with the file extension XML. Binary files are smaller, typically half the size of XML files, and much faster to load and save. Results files can be quite large, so this is not a trivial concern.

However, binary files can only be read by the PACT Result Viewer. In addition, binary files have been reported to cause out of memory errors when being saved or loaded. XML files, while much larger, can be read by any text editor, and can easily be parsed and manipulated by other programs. Either file format contains the original project file, all the fragilities used by that project, and all the result information, including every single analysis, realization, performance group, damage state, and even every random number used in any calculation.

C.11.3 Fragility Specification Files

Fragility specifications are directories and XML files that bear the same identifier as the fragility specification they represent. For each fragility specification, there is a folder with the same name as the fragility ID, containing an XML file and any representative photos of the damage states associated with the fragility function. These folders are stored in a subfolder under the folder where PACT is installed. If the default path was used for installing PACT, these files may be found in the data directory in “ATCCurves.” PACT will show any proper fragility specification stored in this subfolder.

C.11.4 Population Specification Files

Population specification files are saved in XML files bearing the name of the population specification. They are stored in a subfolder under the folder where PACT is installed. If the default path was used for installing PACT, these files may be found at “Templates\Occupancy.”

C.11.5 Reporting Template Files

A Word 2007/2010 file is used as a template. The file must be in the DOCX format; older Word DOC file types will not work. The default location for the template files is in the data folder at “Reports.” It uses mail merge fields in the template as placeholders for putting information from the actual project. Each merge field in the body and header/footer will be reviewed, and if it is in the proper format, will be replaced by values from the Project or Results file. The fields are too many to list out, but the sample templates have all of the available fields, with one exception: If all the fragilities used want to be shown, the field “Special:AllFragilities” should be selected. If only fragilities that are marked as unofficial want to be shown, the alternate merge field of “Special:UnofficialFragilities” can be used.

C.11.6 Programming Notes

PACT is coded using Microsoft Visual Studio 2010 in C#. Besides the functions and utilities contained in the above platform the following third-party controls have been used:

Table C-1 PACT Third Party Controls

Control Name	Vendor	Link
Chart for .NET v. 9.11.3.12 used under commercial license	Nevron Software	http://www.nevron.com/
Math.NET Iridium LPGL open source license	Numeric Foundation	http://www.mathdotnet.com/
Log4Net Apache open source license	Apache Logging Services	http://logging.apache.org/

C.11.6.1 Logfiles

The default location for logfiles is the Project directory, located under the PACT main directory. If for any reason they cannot be written to that location, Local Application Data path, which defaults to C:\Documents and Settings\%username%\Local Settings\Application Data in Windows XP or C:\Users\%username%\AppData\Local in Windows 7 will be used, where %username% is the current username. When reporting bugs, the logfile should be sent to aid with tracking down the bugs.

Appendix D

Normative Quantity Estimation Tool User Manual

D.1 Introduction

The *Normative Quantity Estimation Tool* is provided in Volume 3 to assist the user when establishing the quantities of various building components for entry into the building performance model. The tool is limited in its functionality and a detailed user review of the output is necessary.

Normative quantities are an estimate of the quantity of components and contents likely to be present in a building of a specific occupancy on a gross square foot (gsf) basis. The tool requires as input a listing of the floors of the building and the gross area per floor. The tool produces a floor-by-floor list of the suggested component types and the quantities of those components for input into PACT. To facilitate the building definition, the tool includes eight occupancy types (same as those provided in PACT) with default quantity data for the components commonly appearing in that occupancy.

D.2 Usage Notes

The *Normative Quantity Estimation Tool* contains several worksheets displayed as tabs. These are the following:

- **Notes.** This tab summarizes important development information about the tool.
- **Normative Quantity Estimate.** This tab is used for inputting relevant information and obtaining the output.
- **Normative Quantity Database.** This tab contains the tables which can be used to modify the output of the tool in accordance with the specific building being modeled.
- **Alternate Component Matrix.** This tab presents normative quantities for 10th or 90th percentile values for use in the tool.
- **Name Manager.** This tab presents the file hierarchy used in the PACT **Fragility Specification Manager** utility.
- **Fragility Database.** This tab contains a copy of the *Fragility Database*.

In each of the tabs, the user should only change cells with color shading and select options with the radio buttons. Unshaded (white) cells are calculated or created as the tool executes and thus should not be changed or moved. Also, columns or rows of data should not be added or deleted except where specifically noted.

Pop-up notes with comments have been included to further explain options within the workbook. A red triangle at the upper right of a cell indicates the existence of a pop up note. Hovering over the cell will display the note.

The tool uses Excel macros. The macros must be enabled in order for the tool to run. The spreadsheet was created in Excel Office 2010 version 14.0.6106.5005 as a macro enabled Excel file (.xlsm).

D.3 Normative Quantity Estimate Tab

D.3.1 Building Definition Table

Within the **Building Definition** table each floor is defined by its total floor area and up to three occupancies. To define a building, the user first inputs the name of each floor (starting at the roof) as well as the total floor area on each floor. The user then selects the occupancy types present on each floor and assigns a percentage of the total floor area to each occupancy type. If the percentage values do not add up to 100% over three occupancies, the column to the right of the **Building Definition** table will issue a warning. The user must also provide a floor number for later reference in the output summary. The floor name can be any alphanumeric entry; the floor number must be an integer value starting at 1 at the first floor.

D.3.2 Component Summary Matrix

The “Compile” button executes the tool and populates the **Component Summary Matrix** with a floor-by-floor list of component types for input into PACT. The output matrix is ordered by floor, then occupancy type. The data can be organized and filtered using the dropdown options provided in the column headers.

The *Fragility Database* provides a unit of measure for each fragility group, listed here as “Assumed Quantity per component within PACT.” The “Actual Quantity” value reported recognizes this assumed PACT component quantity and multiplies it by the user input building occupancy area and per occupancy unit quantity defined in the **Building Occupancy Component Matrix** provided in the **Normative Quantity Database** tab. The “Actual Quantity” value should be used to confirm that the components selected are appropriate given the building size and quantity of discreet units required.

The **Component Summary Matrix** lists output that is based upon default fragilities and quantities. The user can make more specific selections using the two tables provided in the **Normative Quantity Database** tab, discussed in Section D.4.

The output listed in the **Component Summary Matrix** can be revised by the user to return quantities specific to the building studied by using the additional features listed in Section D.3.3 or the information provided in the **Normative Quantity Database** tab.

D.3.3 Additional Features

The **Normative Quantity Estimate** tab contains four additional data processing features. These features may be enabled using the ratio buttons next to the “Compile” button. Each feature is described below.

D.3.3.1 Processing of Incomplete Data

This option may be selected to allow incomplete data to be eliminated from being listed in the **Component Summary Matrix**. Selecting “Ignore Incomplete Data” will consider any component types with a unit mismatch and eliminate them from the output matrix. This most often occurs when a component has not been assigned to the **Building Occupancy Component Matrix**, or if a component requires cost and consequence data entered by the user. These components require case-by-case consideration to determine quantity and consequence values.

D.3.3.2 Processing of Zero Data

The tool can be set to check if the occupancy category selected produces a component with zero quantity. If the user has chosen to “Exclude Zero Data,” any component types producing zero quantity will not be listed in the **Component Summary Matrix** when the tool is run.

D.3.3.3 Summation of Fragility by Floor

When considering a building with multiple occupancies, certain components such as generators, cooling towers, or elevators may be more appropriately counted if the component is summed across a floor or across the building and input to PACT as single component. For this reason, the tool has the option of summing individual components on a floor-by-floor or total building basis.

On the **Fragility Database** tab, column AB identifies each component to be classified for summation according to the following:

- NO – The component will not be summed.

- FLR – The component will be summed on a floor-by-floor basis.
- BLDG – The component will be summed across the entire building.

The **Normative Quantity Estimate** tab contains an option to sum the components according to their designation in column AB of the **Fragility Database** tab:

- Sum Components by Building and Floor – Components designated as FLR or BLDG are summed on a floor-by-floor basis or across the entire building, respectively.
- Sum Components by Floor – Components designated as FLR or BLDG are summed on a floor-by-floor basis. This option overrides the summation across the entire building.
- List All Components – All components are listed by the floor and occupancy by which they were defined. The summary output is not summed.

Depending upon the summation method chosen by the user, the Occupancy Type and Floor Level of the component will be listed within the **Component Summary Matrix** as according Table D-1.

Table D-1 Summation Presentations in the Component Summary Matrix

Summation Type	Component Summary Matrix	
	Occupancy Type and Number	Floor Number
Sum by Building and Floor	ALL	ALL
Sum by Floor	ALL	Lists the level on which the component exists.
List All Components	Lists the occupancy the component belongs to.	Lists the level on which the component exists.

“ALL” is reported when a component has been summed over multiple occupancies or floors. When entering a summed component into PACT, the user should place the summed component in the most appropriate occupancy or floor given the component type. For example, mechanical units or distribution panels are likely to be placed in a mechanical room on each floor and the sum of all components should be assigned to the floor in question, given an occupancy type appropriate to the room. Components summed on a total building basis, such as cooling towers or generators should be assigned to the floor where this equipment will be installed, and given an occupancy appropriate to this space.

D.3.3.4 Rounding to Integer Quantity

Certain components such as stairs, elevators, and certain mechanical equipment will be installed only in discreet quantities. On the **Fragility Database** tab, column AA identifies fragilities that can only be installed in discreet quantities, such as stairs, elevators, and certain mechanical equipment. When “Round to Integer Unit” radio button is selected, the tool will round the calculated component quantity up to the next integer value. For comparative or study purposes, the user may unselect this option. This setting supersedes the rounding setting noted in the **Fragility Database** tab. If rounding is disabled, the resulting estimates will include fractional quantities of the components and the user will have to evaluate if some level of rounding is appropriate.

D.4 Normative Quantity Database Tab

The **Component Summary Matrix** on the **Normative Quantity Estimate** tab lists output that is based upon default fragilities and quantities. The user can make more specific selections using the two tables discussed below.

D.4.1 Component Definition Table

This table presents the selection of fragility groups referenced by the tool. The **Component Definition Table** is shaded in blue and thus allows for changes by the user.

For example, as a default, four fragility group selections are provided for D2021.011a (piping fragility for cold water piping with a diameter less than 2.5 inches, designed for Seismic Design Category A or B). The user who has information that the building contains large diameter welded steel piping designed for Seismic Design Category D, E, or F, can use the dropdown list available at the end of column E and select the appropriate fragility group (D2051.023a). If this change is made before pressing the “Compile” button to execute the tool, the output in the **Component Summary Matrix** will list the quantity relevant to D2051.023a.

While making selections, it is important to retain consistency with the description of the component category and relevant component unit quantity and value listed in columns K through M in the **Building Occupancy Component Matrix**. Note that some component categories listed in the **Component Definition Table** do not have any fragilities associated with them in the database. These are identified with “none available” in column E.

In some cases, multiple similar components exist within the PACT database providing various per component quantities. For example, chillers are defined with varying levels of cooling between 350 tons and 1000 tons. Once the tool has run, the user should review the resulting discreet quantity components; an alternate component may exist with better agreement with what may actually be used in the building.

D.4.2 Building Occupancy Component Matrix

Buildings of similar type and occupancy were reviewed during the development of this tool and the quantity of each component per occupancy type was bracketed into 10th, 50th, and 90th percentiles. The tool assumes 50th percentile values by default in the **Building Occupancy Component Matrix**. If the user wishes to use values other than the default values, the component quantity values can be edited in the **Building Occupancy Component Matrix**. 10th, 50th, and 90th percentile values of normative quantities are provided in the **Alternate Quantity Data** tab for reference. This matrix also contains entries for some components, such as fixed casework and fume hoods, that do not have provided fragilities.

Glossary

Definitions

Annual frequency of exceedance. The average number of times per year that an event having magnitude larger than a reference value is likely to occur (typically less than 1).

Annualized loss. The average value of loss, per year, over a period of many years.

Backbone curve. A component force-deformation relationship that envelopes either monotonic or cyclic loading response.

Building performance model. An organized collection of data necessary to define building assets that are at risk and vulnerable to the effects of earthquake shaking.

Capacity boundary. A component force-deformation relationship that represents the maximum strength that a component can develop at a given level of deformation; generally equal to the response of the component to monotonic loading.

Casualties. Loss of life, or serious injury requiring hospitalization.

Collapse floor area ratio. The portion of floor area at each level that is subject to collapse in each collapse mode.

Collapse fragility. A mathematical relationship that defines the probability of incurring structural collapse as a function of ground motion intensity.

Collapse mode(s). One or more ways in which a building would be expected to collapse, ranging from partial to complete collapse. Possible collapse modes include single-story collapse, multi-story collapse, or total collapse.

Component. One of many parts, both structural and nonstructural, that together comprise a building.

Conditional probability. The probability that an outcome will occur, given that a particular event occurs or condition exists.

Consequences. The losses resulting from earthquake damage in terms of potential casualties, repair and replacement costs, repair time, and unsafe placarding.

Consequence function. A relationship that indicates the potential distribution of losses as a function of damage state.

Core and shell replacement cost. The cost to replace the basic building structure, exterior enclosure, and mechanical, electrical, and plumbing infrastructure that is typically present in a building before tenant improvements are made, including costs associated with demolition of the damaged building and clearing the site of debris.

Correlation. A mathematical relationship that defines the extent to which the value of one parameter is dependent on the value of one or more other parameters.

Cyclic envelope. A component force-deformation relationship that envelopes the hysteretic behavior of a component in response to cyclic loading.

Damage state. For a particular component, or the building as a whole, a condition of damage associated with a unique set of consequences.

Decision-maker(s). An individual or group responsible for selecting the performance objectives for a performance-based design.

Demand. A parameter that is predictive of component or building damage states, including peak floor (or ground) acceleration, peak component deformation, peak (or residual) story drift, peak floor (or ground) velocity, or peak component force (or stress).

Discount rate. A factor used to indicate the time-dependent value of money in economic analyses.

Dispersion. A measure of uncertainty associated with prediction of the true value of a random, or otherwise uncertain, behavior.

Distribution. A mathematical function describing the statistical probability that elements in a set will have specific values.

Earthquake scenario. A specific earthquake event, defined by a magnitude and geographic location (distance) relative to a building site.

Floor acceleration. At a floor level, the acceleration of the center of mass relative to a fixed point in space.

Floor velocity. At a floor level, the velocity of the center of mass relative to a fixed point in space.

Fragility function. A mathematical relationship that defines the probability of incurring a damage state conditioned on the value of a single demand parameter.

Fragility group. A set of similar building components having the same potential damage characteristics in terms of fragility and consequence functions.

Fragility specification. A detailed description of potential component damage states, fragility functions, and consequence functions.

Fragility unit of measure. The basic unit used as a basis for defining quantities in a fragility group for the purposes of estimating damage and consequences. Components in a fragility group can be defined in individual units of “each,” units of lineal feet (e.g., 1000 LF), units of square feet (e.g., 250 SF), or other units.

Geometric mean (geomean). In characterizing ground motion intensity, the square root of the product of the value of a ground motion parameter in each of two orthogonal directions (i.e., \sqrt{xy}).

Intensity. The severity of ground shaking as represented by a 5%-damped, elastic acceleration response spectrum, or the 5% damped spectral response acceleration at a specific natural period of vibration.

Intensity-based assessment. An assessment of the probable performance of a building subjected to a ground motion of a specified intensity.

Lognormal distribution. A distribution of values, characterized by a median value and dispersion, with the property that the natural logarithm of the values is normally distributed.

Mean. The average value of a parameter (or population of values). If the population of values is normally distributed, the mean will be equal to the median. If the distribution is skewed, the mean may be less than or greater than the median.

Mean recurrence interval. The average amount of time between expected repeat occurrences of an event (e.g., an earthquake scenario or loss), typically expressed in years.

Median. The value of an uncertain parameter (or population of values) that will be exceeded 50% of the time.

Mutually exclusive damage states. A series of related damage states in which the occurrence of any one type of damage will preclude the occurrence of another type of damage.

Net present value. For a particular discount rate, the present value of benefits that will be received in the future, less the associated costs of these benefits, considering the time-dependent value of money.

Normal distribution. A symmetric distribution described by a mean value and standard deviation. When plotted as a probability density function, a normal distribution has the shape of a bell curve.

Normative quantity. An estimate of the quantity of nonstructural components and contents likely to be present in a building of a specific occupancy on a gross square foot basis.

Nonstructural component. A building component that is not part of the structural system.

Performance. The probable damage and resulting consequences as a result of earthquake shaking or other hazards.

Performance function. A statistical distribution that indicates the probability that losses of a specified or smaller magnitude will be incurred as a result of future earthquakes.

Performance group. A subset of components described by a single fragility group that will experience the same demand in response to earthquake shaking.

Performance group quantity. The number of fragility units of measure present in a building, in the performance group under consideration.

Performance measure. A means of quantifying the consequences associated with earthquake shaking in terms that are meaningful to decision-makers. Performance measures include casualties, repair and replacement costs, repair time, and unsafe placarding.

Performance objective. An expectation as to the probable damage state and resulting consequences that a building may experience in future earthquakes.

Period. The time, in seconds, necessary for a structure to complete one cycle of motion in free vibration.

Probable Maximum Loss. The probable cost of repairing earthquake damage expressed as percentage of building replacement cost with a particular confidence of non-exceedance, conditioned on a particular earthquake return period.

Realization. One possible performance outcome for a particular earthquake scenario or intensity comprising a unique set of demands, damage states, and consequences.

Repair cost. The cost, in present dollars, necessary to restore a building to its pre-earthquake condition, or in the case of total loss, to replace the building with a new structure of similar construction.

Repair fragility. A mathematical relationship that defines the probability that a building will be considered irreparable as a function of residual drift ratio.

Repair time. The time, in weeks, necessary to repair a damaged building to its pre-earthquake condition.

Replacement cost. The cost, in present dollars, necessary to replace a building that has been damaged beyond the point of practicable repair, including costs associated with demolition and removal of debris.

Replacement time. The time, in weeks, necessary to replace a building that has been damaged beyond the point of practicable repair, including time associated with demolition and removal of debris.

Residual drift. The difference in permanent displacement between the center of mass of two adjacent floors as a result of earthquake shaking.

Residual drift ratio. Residual drift divided by story height.

Return on investment. The annual income that can be derived from an investment divided by the present value of the investment.

Return period. See mean recurrence interval.

Rugged. Not vulnerable to damage, or having a very high threshold for damage; alternatively, not considered significant for assessing seismic performance impacts.

Scenario-based assessment. An assessment of the probable performance of a building subjected to a specified earthquake scenario.

Scenario Expected Loss. A probable maximum loss with mean chance of occurrence.

Scenario Upper Loss. A probable maximum loss with a 10% chance of exceedance.

Seismic hazard curve. A plot of the annual frequency of exceedance of the possible values of a ground shaking intensity parameter.

Sequential damage states. A series of related component damage states that must occur in sequence following the occurrence of an initial damage state.

Simulated demands. A vector set of demands representing the building response in a particular realization, reflecting the correlation between the various response quantities predicted in the structural analyses and uncertainties inherent in structural response prediction.

Simultaneous damage states. A series of independent and unrelated component damage states that can occur, but need not necessarily occur, at the same time.

Stakeholder(s). An individual or group affected by the performance of a building, including building owners, lenders, insurers, tenants, and the general public.

Story drift. The instantaneous difference in lateral displacement between the center of mass of two adjacent floors.

Story drift ratio. Story drift divided by story height.

Structural component. A building component that is part of the intended gravity or seismic-force-resisting system, or that provides measurable resistance to earthquake shaking.

Structural system. A collection of structural components acting together in resisting gravity forces, seismic forces, or both.

Time-based assessment. An assessment of the probable performance of a building, considering all earthquake scenarios and the associated probability of occurrence of each, over a specified period of time.

Total loss threshold. A user-defined cap on the level of repair effort at which a building is likely to be replaced rather than repaired.

Total replacement cost. The cost to replace an entire building (core, shell, and tenant improvements) as it exists in its pre-earthquake condition, including costs associated with demolition of the damaged building and clearing the site of debris.

Unsafe placarding. A post-earthquake inspection rating that deems a building, or portion of a building, damaged to the point that entry, use, or occupancy poses immediate risk to safety. Unsafe placards are typically colored red.

Yield drift. The value of drift at which a structure reaches its effective yield strength.

Yield story drift. The value of story drift at which a story in a structure reaches its effective yield strength.

Yield story drift ratio. Yield story drift divided by story height.

Symbols

Notation

a_i^*	in the simplified analysis method, estimated median peak floor acceleration at level “ i ”
b	slope of a straight line fit to a series of data having x and y values
c	y intercept of a straight line fit to a series of data having x and y values
d_i	value of the demand at which a particular damage state was first observed to occur in specimen “ i ” in a series of m tests, or the maximum value of demand to which a specimen was subjected without occurrence of the damage state
\bar{d}_j	maximum demand experienced by a series of test specimens in bin “ j ”
d_{max}	maximum demand, d , experienced by a specimen in a series of tests
d_{min}	for a series of tests of specimens, the minimum value of demand, d , at which any specimen exhibited damage or distress
e_i	in time-based assessment the mid-range intensity within an incremental range of intensities, Δe_i
f_r	rocking frequency of an unanchored object, (hz)
f_s	frequency associated with sliding of an unanchored object, (hz)
h	building height (also designated as H)
h_i	in the simplified procedure, the height of level “ i ” above the building base
i	interest rate, or expected rate of return on money
k	in the simplified procedure, a coefficient used to account for nonlinear mode shape
m_j	number of specimens in bin “ j ” for which damage conforming to a particular damage state is observed
t	period of years over which an investment decision is amortized

v_i^*	in the simplified analysis method, estimated median peak floor velocity at level “ i ”
v_{si}	reference floor velocity parameter used to determine estimated peak floor velocity in the simplified analysis procedure
w_j	in simplified analysis, weight lumped at a structure’s level “ j ”
x_j	natural logarithm of \bar{d}_j
\bar{x}	mean value of a series of values, x_j
y_j	inverse lognormal distribution value for the number of specimen tests that experienced a damage state in a bin “ j ” of specimen tests
\bar{y}	mean of the values of y_j
A	amount of money that is earned or expended each year over a period of several years
B	parameter used to calculate the critical tipping demand on an unanchored object
C_1	in the simplified analysis procedure, a coefficient used to account for the difference in displacement response between elastic and inelastic structures, assuming non-degrading inelastic behavior
C_2	in the simplified analysis procedure, a coefficient used to account for the effects of stiffness degradation on displacement response
C_3	coefficient used to determine the rocking capacity of an unanchored object
C_q	coefficient that adjusts computed median strength capacity for construction quality
C_R	coefficient used to determine the rocking capacity of an unanchored object
C_{sm}	coefficient used to derive an approximate estimate of the fraction of total mass effective in first mode response
C_{vx}	in the simplified analysis procedure, the fraction of the total pseudo lateral force, applied to level “ x ”
D_{amp}	spectral velocity amplification factor
F_x	in the simplified analysis procedure, the pseudo lateral force applied to level “ x ”
H	total building height above the base; also, the height of a wall panel
M	total number of test specimens for which test data is available and for which the damage state of interest occurred

M_A	in a series of M tests, the number of specimens that did not experience any damage or distress but which experienced demands greater than or equal to a reference value, d_a
M_B	in a series of M tests, the number of specimens that experienced some damage or distress but which did not experience the damage state of interest
M_j	number of test specimens in a bin “ j ” of a series of tests
N	total number of vulnerable stories in a building performance model
NPV	net present value of a future stream of incomes or expenditures
PGA	peak ground acceleration, (g)
PGV	peak ground velocity, (in/sec)
PM_{10}	value of a performance measure (e.g., repair cost) with a 10% chance of exceedance
PM_{50}	median value of a performance measure (e.g., repair time) with a 50% of exceedance
PM_{90}	value of a performance measure (e.g., casualties) with a 90% chance of exceedance
\overline{PM}	mean value of a performance measure, also known as the expected value or average value
$P(C)$	conditional probability of building collapse, given an intensity of shaking
$P(U_i)$	probability, for a given intensity or scenario, that damage sustained by components in performance group “ i ” will result in an unsafe placard
$P(U_T)$	total conditional probability, given a specific intensity of motion or earthquake scenario, that a building will receive an unsafe placard
P_{EY}	probability of exceedance of an event in Y years
P_R	mean return period for an event
R	number of realizations in a performance assessment
R_n	nominal resistance in accordance with load and resistance factor design (LRFD) specifications
S	in the simplified analytical procedure, the ratio of elastic base shear force to the structure’s yield shear strength
$S_a(T)$	spectral response acceleration at period T , (g)

$\hat{S}_a(T)$	median collapse capacity of a structure, measured in terms of spectral response acceleration at period T , (g)
S_a^{max}	for time-based assessment, the maximum spectral response acceleration at which performance is assessed, (g)
S_a^{min}	for time-based assessment, the minimum spectral response acceleration at which performance is assessed, (g)
S_{aD}	effective value of design spectral acceleration at which a structure satisfies all applicable seismic design criteria of ASCE/SEI 7-10, (g)
S_{aO}	spectral acceleration that will tip an unanchored object to a critical angle at which overturning instability will occur, (g)
$S_{gm}(T)$	geometric mean (geomean) spectral response acceleration at period T , (g)
$S_v(1)$	spectral velocity at a period of 1 second
T	period of structural response, i.e., the amount of time that a structure in free vibration will take to complete one cycle of motion, (sec)
T_l	period of fundamental mode of vibration
T_l^X	period of fundamental mode of translation along the horizontal X axis
T_l^Y	period of fundamental mode of translation along the horizontal Y axis
\bar{T}	average of the periods of the fundamental mode of translation along each of two orthogonal building axes
T_{max}	maximum period in a range of periods used to scale ground motions for nonlinear response history analysis
T_{min}	minimum period in a range of periods used to scale ground motions for nonlinear response history analysis
V	in the simplified analysis procedure, a pseudo lateral force used to estimate story drifts
V_s	average shear wave velocity of soil in the upper 100 feet (30 meters)
V_{PT}	peak total floor velocity at a floor level, in/sec
V_{yt}	effective yield strength of a structure responding in the first mode
W_l	in simplified analysis, the first mode weight effective of a structure
Y	number of years considered in a time-based assessment

α	for an unanchored object, the critical tip angle at which the object will become unstable and overturn, radians
β	measure of dispersion in the true value of a random parameter, also called uncertainty
β_a	uncertainty associated with analysis record-to-record response variability
β_{aa}	in the simplified analysis procedure, default record-to-record variability (dispersion) associated with floor acceleration response
β_{av}	in the simplified analysis procedure, default record-to-record variability (dispersion) associated with floor velocity response
$\beta_{a\Delta}$	in the simplified analysis procedure, default record-to-record variability (dispersion) associated with story drift response
β_c	modeling uncertainty associated with ambiguity in details of construction; also, the uncertainty associated with estimates of repair cost
β_C	in calculation-based fragilities, uncertainty associated with the quality of installation (or construction) of a component
β_D	uncertainty associated with the ability of a design equation to predict actual behavior when material strength is defined
β_{FA}	in the simplified analysis procedure, the total dispersion associated with floor acceleration
β_{FV}	in the simplified analysis procedure, the total dispersion associated with floor velocity
β_{gm}	dispersion accounting for uncertainty in ground motion intensity as reflected in attenuation relationships
β_m	modeling uncertainty associated with dispersion in the predicted response from structural analysis
β_M	uncertainty in material strength
β_q	modeling uncertainty associated with the quality and completeness of the nonlinear analysis model, considering component hysteretic modeling, estimates of damping, and the number of elements included in the model
β_r	in a series of data used to establish fragility functions, the random variability evident in the data; also, the damping ratio for a rocking object (fraction of critical damping)

β_{SD}	in the simplified analysis procedure, the total dispersion associated with story drift
β_u	in a series of data used to establish fragility functions, a measure of uncertainty representing differences between the conditions inherent in the data set and actual conditions present in a real building
δ	sliding displacement that will cause an unanchored component to hit another object, resulting in damage
δ_i	peak displacement of floor “ <i>i</i> ” relative to the base
δ_r	peak displacement of the roof relative to the base
δ_y	component deformation at yield
γ	factor used to determine effective damping for a rocking component
Δ_i	in the simplified procedure, the uncorrected story drift ratio at level “ <i>i</i> ”
Δ_i^*	estimated median peak story drift ratio at story “ <i>i</i> ”
Δ_r	estimated median residual story drift ratio
Δe_i	in time-based assessments, an incremental range of earthquake intensities
$\Delta \lambda_i$	in time-based assessments, the probability of occurrence in a period of time, for earthquake intensity in range Δe_i
Δ_y	estimated story drift at development of yield strength
θ	in lognormal distributions, the median value of demand
θ_{DS}	in lognormal distributions, the median value of demand
λ	mean annual frequency of exceedance of a ground motion parameter
μ	ratio of component deformation at onset of damage, to component deformation at yield
μ_D	kinetic coefficient of friction between an unanchored object and its resting surface
μ_S	static coefficient of friction between an unanchored object and its resting surface
ϕ	resistance factor, as specified in load and resistance factor design (LRFD) specifications
ϕ_j	in simplified analysis, the ordinate of the first mode deflection at floor level “ <i>j</i> ”

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