EARTHQUAKE LOSS ESTIMATION METHODOLOGY

Hazus®-MH 2.1

Advanced Engineering Building Module (AEBM)

Technical and User's Manual

Developed by:
Department of Homeland Security
Federal Emergency Management Agency
Mitigation Division
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This manual is available on the FEMA website at www.fema.gov/plan/prevent/hazus.

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EXECUTIVE SUMMARY

This manual describes procedures for developing building-specific damage and loss functions with the Advanced Engineering Building Module (AEBM). The AEBM procedures are an extension of the more general methods of the FEMA earthquake loss estimation methodology (*Hazus*) and provide damage and loss functions compatible with current *Hazus-MH Software*. Kircher & Associates working for the National Institute of Building Sciences (NIBS) has developed these procedures under agreements between NIBS and the Federal Emergency Management Agency (FEMA). The procedures have been pilot tested and reviewed by NIBS' Earthquake Committee and Building Damage Subcommittee.

Hazus damage and loss functions for generic model building types are considered to be reliable predictors of earthquake effects for large groups of buildings that include both above median and below median cases. They may not, however, be very good predictors for a specific building or a particular type of building that is known to have an inherent weakness or earthquake vulnerability (e.g., W1 buildings with weak cripple walls would be expected to perform much worse than typical wood-frame buildings).

For mitigation purposes, it is desirable that users be able to create building-specific damage and loss functions that could be used to assess losses for an individual building (or group of similar buildings) both in their existing condition and after some amount of seismic rehabilitation. The term "building-specific" distinguishes the development of damage and loss functions, as described in this manual, from the "generic" building functions of *Hazus*. Building-specific damage and loss functions are based on the properties of a particular building. The particular building of interest could be either an individual building or a typical building representing a group of buildings of an archetype.

The procedures are of a highly technical nature, and users should be qualified seismic/structural engineers who, for example, might be advising a local jurisdiction regarding the merits of adopting an ordinance to require cripple-wall strengthening of older wood-frame residences. The accuracy of damage and loss estimates using building-specific functions, and their improvement over predictions using generic building functions, will depend both on the quality and completeness of building-specific data and on ability of the user to transform this information into meaningful functions. The accuracy of damage and loss estimates for a group of buildings will also depend on the ability of the user to select a typical building that represents the archetype of interest.

Users should have some background and experience in actual earthquake performance of buildings, be familiar with special seismic analysis (e.g., pushover) methods and be able to envision building damage patterns and failure modes. Even though the procedures are quite detailed, users will still need to apply judgment in the development of building-specific damage and loss functions.

To facilitate easier implementation of building-specific methods by users, an Advanced Engineering Building Module (AEBM) has been added to the *Hazus-MH Software*. Some parameters and indeed some methods of loss calculation of the new AEBM are different than those of other modules of *Hazus*. Revision 2 of this manual describes parameters and methods that are consistent with the new AEBM, even though some terms may not be fully documented in the *Hazus-MH 2.1 Technical Manual* [FEMA, 2001b]. Revision 2 also includes an example application of the AEBM in Section 8 of the manual.

The example application in Section 8 of this manual provides users with a step-by-step description of the calculation of building damage and loss using the AEBM. The example illustrates both the transformation of engineering data (e.g., pushover analysis results) into AEBM parameters (e.g., capacity and fragility curve parameters), and the implementation of these parameters using the AEBM of the *Hazus-MH 2.1 Software*. The example calculates damage and loss for a large, welded steel moment frame (WSMF) building in its current (original building) configuration and the calculation of damage and losses for the WSMF building with connections strengthened to avoid premature fracturing and failure. In both cases, damage and losses are calculated for the same level of ground shaking that is based on a magnitude M7.2 scenario earthquake on the Sierra Madre fault, the fault that dominates seismic hazard at the example building site.

CHAPTER 1

INTRODUCTION

1.1 Scope and Background

This manual describes procedures for developing building-specific damage and loss functions with the Advanced Engineering Building Module (AEBM). The AEBM procedures are an extension of the more general methods of the FEMA/NIBS earthquake loss estimation methodology (*Hazus*) and provide damage and loss functions compatible with current *Hazus-MH 2.1 Software*. Kircher & Associates working for the National Institute of Building Sciences (NIBS) has developed these procedures under agreements between NIBS and the Federal Emergency Management Agency (FEMA). The procedures have been pilot tested and reviewed by NIBS' Earthquake Committee and Building Damage Subcommittee.

The FEMA/NIBS earthquake loss estimation methodology, commonly known as *Hazus*, is a complex collection of components that work together to estimate casualties, loss of function and economic impacts on a region due to a scenario earthquake. The methodology is documented in the *Hazus-MH 2.1 Technical Manual* [FEMA, 2001b]. One of the main components of the methodology estimates the probability of various states of structural and nonstructural damage to buildings. Damage state probabilities are used by other components of the methodology to estimate various types of building-related loss. Typically, buildings are grouped by model building type and evaluated on a census tract basis.

Currently, *Hazus* includes building damage functions for 36 model building types (and for various combinations of seismic design level and performance). Each model building type represents a "generic" group of buildings that share a common type of construction (e.g., W1 represents smaller wood-frame buildings) and a common seismic design level (e.g., Moderate-Code represents buildings of current *Uniform Building Code* Seismic Zone 2 design or older buildings of Seismic Zone 3 or 4 design).

Damage and loss functions for generic building types are considered to be reliable predictors of earthquake effects for large groups of buildings that include both above median and below median cases. They may not, however, be very good predictors for a specific building or a particular type of building that is known to have a weakness or earthquake vulnerability (e.g., W1 buildings with weak cripple walls would be expected to perform much worse than typical wood-frame buildings). Although the theory is applicable to an individual building, building-specific damage and loss functions are not provided and would need to be developed by the user. The complexity of the methods and underlying seismological and engineering phenomena makes development of building-specific functions challenging unless the user is an engineer experienced in nonlinear seismic analysis (and seldom necessary for regional loss estimation studies).

For mitigation purposes, it is desirable that users be able to create building-specific damage and loss functions that could be used to assess losses for an individual building (or group of similar buildings), both in their existing condition and after some amount of seismic rehabilitation. "Users" in this context refer to seismic/structural engineers who, for example, might be advising a local jurisdiction regarding the merits of adopting an ordinance to require cripple-wall strengthening of older wood-frame residences.

FEMA/NIBS projects in the area of earthquake hazard mitigation also include the Building Seismic Safety Council's (BSSC's) development of the *NEHRP Guidelines for Seismic Rehabilitation of Buildings* [FEMA, 1997], referred to simply as the *NEHRP Guidelines*. Like *Hazus*, the *NEHRP Guidelines* represent a major, multi-year effort. Also like *Hazus*, the *NEHRP Guidelines* use similar earth science theory and engineering techniques. For the first time, earthquake loss estimation and building seismic analysis are based on common concepts. For example, both the FEMA/NIBS methodology and the *NEHRP Guidelines* (1) use the same characterization of ground shaking (i.e., response spectra, as defined by the USGS maps/theory) and (2) use the same nonlinear (pushover) characterization of building response. The similarity of these fundamental concepts permits interfacing the methods of the *NEHRP Guidelines* with those of *Hazus* for development of building-specific damage and loss models.

1.2 Purpose and Approach

The primary purpose of the AEBM is to support mitigation efforts by providing building-specific loss estimation tools for use by experienced seismic/structural engineers. To produce accurate results, the engineer must be capable of carrying out a relatively sophisticated pushover analysis as described below. While the expertise and required inputs may seem challenging, building-specific methods are intended for use by those experts who have the requisite skills and desire to go beyond the default methods and data of the more user-friendly “Level 1” or “Level 2” procedures of *Hazus*.

The underlying approach of AEBM procedures is a combination of the nonlinear static (pushover) analysis methods of the *NEHRP Guidelines* (and other sources, namely the *ATC-40* document: *Seismic Evaluation and Retrofit of Concrete Buildings*, CSSC, 1996) with *Hazus* loss estimation methods. Seismic/structural engineers having performed a detailed pushover analysis of a specific building are expected to have a much better understanding of the building’s potential failure modes, overall response characteristics, structural and nonstructural system performance, and the cost and time required to repair damaged components.

The *NEHRP Guidelines* provide a logical and appropriate starting point for seismic evaluation of existing buildings and provide state-of-the-art techniques, such as pushover analysis. The *NEHRP Guidelines* also provide limit state criteria for elements and components of buildings that are useful to engineers for determining building-specific damage states. Detailed investigation of a specific building should also provide other important loss-related information. For example, building owners would be expected to provide much more reliable estimates of total replacement cost (value) of the building, the extent and value of contents or inventory, and number of building occupants during different times of the day. All these are critical data required for reliable estimates of earthquake losses.

1.3 Pilot Testing and Revision of the Manual

An initial draft of this manual (October 1999) was evaluated during the year 2000 by two separate pilot studies [Reis, 2000 and EQE, 2000]. Based on the findings of these studies, the Earthquake Committee of NIBS recommended certain improvements to building-specific methods and the development of a new Advanced Engineering Building Module to facilitate easier implementation of building-specific methods in the *Hazus* software.

Revision 1 of this manual (March 2001) incorporated improvements to building-specific methods recommended by the Earthquake Committee and updated descriptions of parameters and methods that are consistent with the "Beta" version of new AEBM (January 2001).

Revision 2 of this manual (January 2002) incorporates changes to the final version of the AEBM (and other updated modules) of the *Hazus-MH 2.1 Software*. Some parameters and indeed some methods of loss calculation of the new AEBM are different than those of other modules of the *Hazus*. Revision 2 of this manual describes parameters and methods that are consistent with the new AEBM, even though some terms may not be fully documented in the *Hazus-MH 2.1 Technical Manual*. Revision 2 also includes an example application of the AEBM in Section 8 of this manual.

1.4 Individual Buildings and Groups of Buildings of a Specific Type

The term "building-specific" distinguishes the development of damage and loss functions, as described in this manual, from the "generic" building functions of *Hazus*. Building-specific damage and loss functions are based on the properties of a particular building. The particular building of interest could be either an individual building or a typical building representing a group of buildings of an archetype (e.g., wood frame residences with weak cripple walls). Throughout this manual, the term "the building" refers to a typical building of a group of buildings of an archetype, as well as to an individual building.

In the most complete sense, development of building-specific properties for a group of buildings would involve modeling and pushover analysis of a suite of structures that fairly represent the range of configurations and properties of the building group of interest. Results of the analyses could then be statistically evaluated to produce estimates of the distribution of the parameter of interest (e.g., estimates of median value and variability of building capacity). In general, this approach is neither practical nor warranted for most applications. The methods described in this manual assume that a typical building or theoretical archetype is selected by the user to represent the group of buildings of interest.

Results of the analysis of the typical building represent median properties of the group. Parameter variability is based on judgement considering the number and similarity of buildings in the group. Small groups of very similar buildings would have parameter variability commensurate with that of an individual building. Large or dissimilar-building groups would have parameter variability commensurate with that of the generic building types of *Hazus*.

Guidance is provided in Section 6 for development of damage-state variability considering the size and conformity of buildings in the group of buildings of interest.

1.5 AEBM Overview

The Advanced Engineering Building Module (AEBM) implements building-specific methods in the *HAZUA99-SR2 Software* through a variety of *Hazus* software menus and dialog boxes that begin with defining a study region, include defining ground shaking hazard and AEBM inventory, running AEBM analyses and finally viewing or printing of AEBM results. Figure 1.1 illustrates the flow of *Hazus* software elements related to the AEBM.

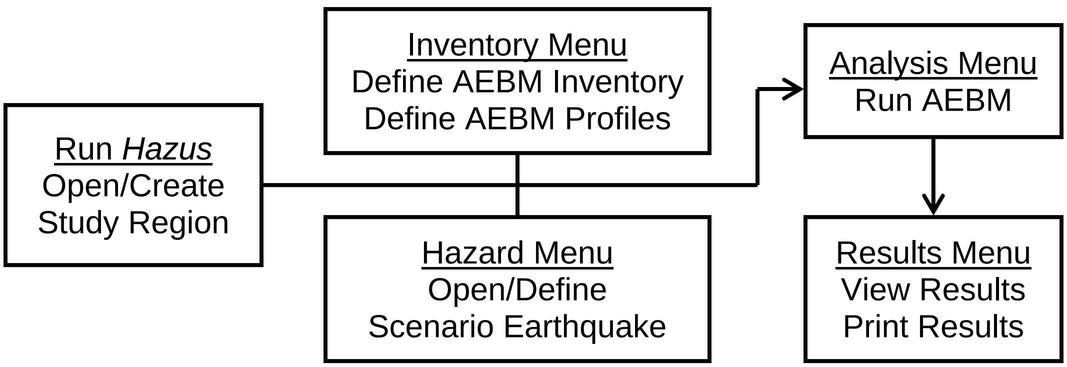


Figure 1.1. *Hazus* Software - Flowchart of AEBM Calculation of Damage and Loss

The software architecture of the AEBM has two main components (or databases), AEBM Inventory and AEBM Profiles. AEBM Inventory is structured to accept a "portfolio" of individual buildings each uniquely defined by (latitude/longitude) location, number of occupants, size, replacement cost and other building-specific financial data. The AEBM Profiles describe an extensive set building performance characteristics, including damage and loss function parameters. Each building in the AEBM Inventory must be linked to one of the AEBM Profiles to run the AEBM, but an AEBM Profile can be used for more than one building of the AEBM Inventory. Applications of the AEBM include evaluation of individual buildings or a group of buildings of a similar type, as described below.

- Evaluation of Individual Building(s) – In this case, the user creates an AEBM Inventory record and an AEBM Profiles record (linked to the AEBM Inventory record) for each individual building of interest. These sets of linked inventory and profile data define unique properties for each individual building of interest.

  In Section 8 of this manual, the AEBM evaluates two "individual" buildings that represent the same building before and after seismic strengthening. In this example, the two records in the AEBM Inventory contain the same data (i.e., same building location, population and replacement value), but the two AEBM Profile records reflect differences in performance characteristics before and after seismic rehabilitation. Comparison of the AEBM results, before and after strengthening, provides a measure of the benefits of seismic mitigation.

- Evaluation of a Group of Similar Buildings – In this case, the user creates an AEBM Inventory record for each building of the group, distributing them by (latitude/longitude) location throughout the study region, and a single AEBM Profile record (linked to each building of the group). These profile data define properties that represent the collective performance of the group (i.e., building type).

  An example "group" application of the AEBM is the evaluation of a "new" building type, not well represented by an existing building type of *Hazus* (e.g., URM buildings seismically-strengthened to meet certain performance criteria). The building-specific methods described in this manual may be used to create "customized" model building types, such as "strengthened URM" buildings, and the AEBM can be used to evaluate damage and loss to these buildings. For a regional study, the AEBM Inventory would locate representative inventory at the centroid of each census tract of the study region.

1.6 Manual Organization

The balance of this manual begins in Section 2 with a summary of *Hazus* earthquake loss estimation methods for readers not familiar with *Hazus*. This section includes material from the *Hazus-MH 2.1 Technical Manual* and from papers published in *Earthquake Spectra* that describe building damage and loss methods [Whitman et al., 1997, Kircher et al., 1997a, Kircher et al. 1997b].

Sections 3 and 4 summarize the type and format of data that are used in the AEBM to estimate building damage and loss. Section 3 describes building-specific data that must be provided by users, including site hazard information, performance properties and cost and occupant data. Section 4 describes the type and format of damage and loss parameters used by the Advanced Engineering Building Module (AEBM) of the *Hazus99-SR-2 Software*.

Procedures for developing AEBM capacity curves (and related response parameters), AEBM fragility curves and AEBM loss functions from building-specific data are described in Sections 5, 6 and 7, respectively. Section 5 methods provide guidance for the user's selection of capacity curve control points and other response parameters from the results of an existing nonlinear static (pushover) analysis of the building. Section 6 methods describe development of fragility curve properties (i.e., median value and variability of damage states). Median values of structural damage states are also based on the results of the building's pushover analysis, while damage-state variability is selected from pre-calculated values that are tabulated as a function of key building characteristics. Section 7 methods help users develop functions that relate social and economic losses to building damage.

Section 8 illustrates application of building-specific procedures with a step-by step example calculation of building damage and loss using the AEBM. The example illustrates both the transformation of engineering data (e.g., pushover analysis results) into AEBM parameters (e.g., capacity and fragility curve parameters), and the implementation of these parameters using the AEBM of the *Hazus-MH 2.1 Software*. The example calculates damage and loss for a large, welded steel moment frame (WSMF) building in its current (original building) configuration, and the calculation of damage and losses for the WSMF building with connections strengthened to avoid premature fracturing and failure. In both cases, damage and losses are calculated for the same level of ground shaking that is based on a magnitude M7.2 scenario earthquake on the Sierra Madre fault, the fault that dominates seismic hazard at the example building site.

SECTION 2

SUMMARY OF *Hazus* EARTHQUAKE LOSS ESTIMATION METHODS

2.1 Overview of Methodology

The FEMA/NIBS earthquake loss estimation methodology, commonly known as *Hazus*, has many components, or modules, as described in the *Hazus-MH 2.1 User's Manual* [FEMA, 2001c] and *Hazus-MH 2.1 Technical Manual* [FEMA, 2001b]. Other sources of information on *Hazus* include *Earthquake Spectra* papers: "Development of a National Earthquake Loss Estimation Methodology" [Whitman et al., 1997], "Development of Building Damage Functions for Earthquake Loss Estimation [Kircher et al., 1997a] and " Estimation of Earthquake Losses to Buildings" [Kircher et al., 1997b]. The user should have copies of the *Hazus-MH 2.1 User's Manual* and *Hazus-MH 2.1 Technical Manual* for reference and be familiar with *Hazus* methods before attempting to develop building-specific damage and loss functions.

The flow of the *Hazus* methodology between those modules related to building damage and loss is illustrated in Figure 2.1. Inputs to the estimation of building damage include ground shaking and ground failure, characterized by permanent ground deformation (PGD) due to settlement and lateral spreading. This manual describes building-specific methods for estimating damage and loss due to ground shaking, typically the dominant contributor to building-related losses.

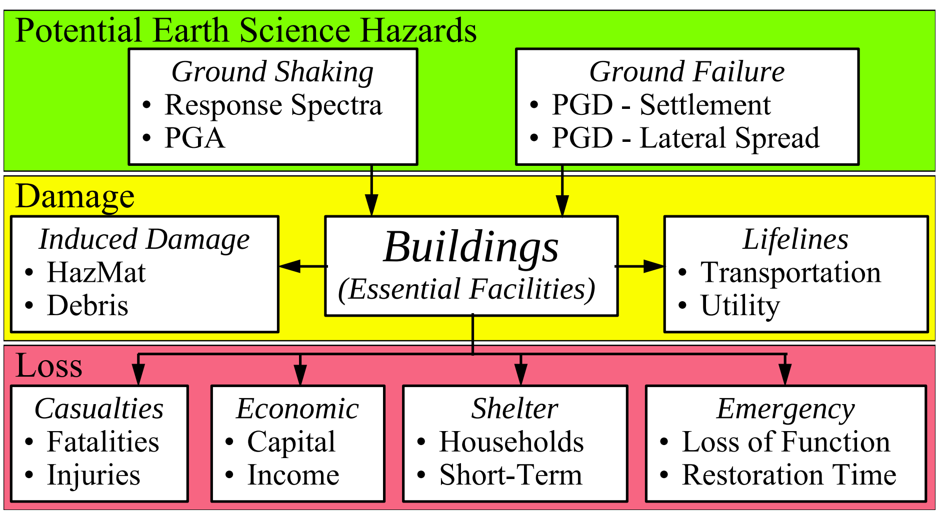


Figure 2.1. Building-Related Modules of the FEMA/NIBS Methodology

Estimates of building damage are used as inputs to other damage modules, including hazardous materials facilities (HazMat) and debris generation, and as inputs to transportation and utility lifelines that have buildings as a part of the system (e.g., airport control tower). Most importantly, building damage is used as an input to a number of loss modules, including the estimation of casualties, direct economic losses, displaced households and short-term shelter needs, and loss of emergency facility function and the time required to restore functionality.
Hazus damage functions for ground shaking have two basic components: (1) capacity curves and (2) fragility curves. The capacity curves are based on engineering parameters (e.g., yield

and ultimate strength) that characterize the nonlinear (pushover) behavior of 36 different model building types. For each of these building types, capacity parameters distinguish between different levels of seismic design and anticipated seismic performance. The fragility curves describe the probability of damage to the building's: (1) structural system, (2) nonstructural components sensitive to drift and (3) nonstructural components (and contents) sensitive to acceleration. For a given level of building response, fragility curves distribute damage between four physical damage states: Slight, Moderate, Extensive and Complete.

Earthquake loss due to building damage is based on the physical damage states that are deemed to be the most appropriate and significant contributors to that particular type of loss. For example, deaths are based primarily on the Complete state of structural damage, since partial or complete collapse of the building is assumed to dominate this type of loss. In contrast, direct economic loss (e.g., repair/replacement cost) is accumulated from all states of damage to both structural and nonstructural systems, since all are significant contributors to economic loss.

2.2 Building Classification

Buildings are classified both in terms of their use, or occupancy class, and in terms of their structural system, or model building type. Damage is predicted based on model building type, since the structural system is considered the key factor in assessing overall building performance, loss of function and casualties. Occupancy class is important in determining economic loss, since building value is primarily a function of building use (e.g., hospitals are more valuable than most commercial buildings, primarily because of their expensive nonstructural systems and contents, not because of their structural systems).

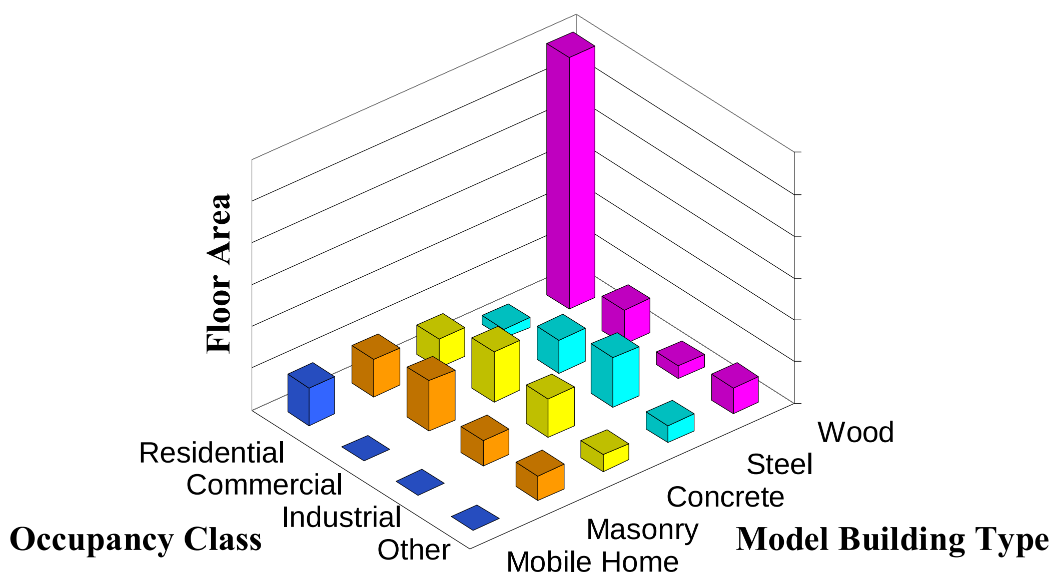


Figure 2.2. Example Inventory Relationship of Model Building Type and Occupancy Class

Table 2.1. Model Building Types of *Hazus*

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	Wood, Light Frame (≤ 5,000 sq. ft.) Wood, Greater than 5,000 sq. ft.		All All	1 2	14 24
3 4 5	S1L S1M S1H	Steel Moment Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	Steel Braced Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 13	24 60 156
9	S3	Steel Light Frame		All	1	15
10 11 12	S4L S4M S4H	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 13	24 60 156
13 14 15	S5L S5M S5H	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	Concrete Moment Frame	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 12	20 50 120
25	PC1	Precast Concrete Tilt-Up Walls		All	1	15
26 27 28	PC2L PC2M PC2H	Precast Concrete Frames with Concrete Shear Walls	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 12	20 50 120
29 30	RM1L RM1M	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise Mid-Rise High-Rise	1-3 4-7 8+	2 5 12	20 50 120
34 35	URML URMM	Unreinforced Masonry Bearing Walls	Low-Rise Mid-Rise	1-2 3+	1 3	15 35
36	MH	Mobile Homes		All	1	10

Twenty-eight occupancy classes are defined to distinguish among residential, commercial, industrial or other buildings; and 36 model building types are used to classify buildings within the overall categories of wood, steel, concrete, masonry or mobile homes. Building inventory data relate model building type and occupancy class on the basis of floor area, as illustrated in Figure 2.2, so that for a given geographical area the distribution of the total floor area of model building types is known for each occupancy class. For presentation purposes, Figure 2.2 shows only the four overall categories of occupancy and the five overall categories of construction, whereas FEMA/NIBS methodology calculations are based on all 28 occupancy classes and 36 model building types.

Model building types are derived from the same classification system that is used in the *NEHRP Handbook for the Seismic Evaluation of Buildings – A Prestandard* [FEMA, 1998], but expanded to include mobile homes and to consider building height. Table 2.1 describes model building types and their heights. Typical building heights are used in the determination of generic-building capacity curve properties.

2.3 Seismic Design Levels and Quality of Construction

The building damage functions distinguish among buildings that are designed to different seismic standards, have different construction quality, or are otherwise expected to perform differently during an earthquake. These differences in expected building performance are determined primarily on the basis of seismic zone location, design vintage and use (i.e., special seismic design of essential facilities).

The 1994 *Uniform Building Code* [ICBO, 1994] was used to establish differences in seismic design levels, since at the present time the 1994 *UBC* or earlier editions of this model code likely governed the design, if the building was designed for earthquake loads. For the purpose of loss estimation, buildings designed in accordance with the 1994 *NEHRP Provisions* [FEMA, 1995] are assumed to have the same damage functions to buildings designed to meet the 1994 *UBC* (when *NEHRP* map area and *UBC* seismic zone criteria are similar). Damage functions are provided for three "Code" seismic design levels, labeled as High-Code, Moderate-Code and Low-Code, and an additional design level for Pre-Code buildings. The Pre-Code design level includes buildings built before seismic codes were required for building design (e.g., buildings built before 1941 in California and other areas of high seismicity).

High-Code, Moderate-Code and Low-Code seismic design levels are based on 1994 *UBC* lateral force design requirements of Seismic Zones 4, 2B and 1, respectively. Damage functions for these design levels are directly applicable to modern code buildings of about 1975 or later design vintage. Pre-1975 buildings and buildings of other *UBC* seismic zones are associated with Moderate-Code, Low-Code or Pre-Code design levels, based either on the expertise of the user or on default relationships provided by the FEMA/NIBS methodology. For example, Moderate-Code (rather than High-Code) damage functions are used to estimate damage to *UBC* Seismic Zone 4 buildings built before 1975 (but after 1941). *Hazus* guidelines for selection of damage functions for buildings are given in Table 2.2 based on the buildings age (design vintage) and the applicable seismic code (i.e., as defined by either the seismic zone of the 1994 *UBC* or the map area of the 1994 *NEHRP Provisions*).

The FEMA/NIBS methodology also includes "Special," above-Code, building damage functions for those essential facilities (e.g., post-1973 California hospitals) that are known to be of superior design and construction. Building damage functions for Special buildings are based on the same theory as that of Code buildings, except that the parameters of the capacity and fragility curves reflect greater seismic capacity and reliability of these buildings.

Table 2.2. Recommended Seismic Design Level for Existing Buildings (w/o Retrofit)

UBC Seismic Zone (*NEHRP* Map Area)	Design Vintage		
	Post-1975	1941 - 1975	Pre-1941
Zone 4 (MA 7)	High-Code	Moderate-Code	Pre-Code[1]
Zone 3 (MA 6)	Moderate-Code	Moderate-Code	Pre-Code[1]
Zone 2B (MA 5)	Moderate-Code	Low-Code	Pre-Code[2]
Zone 2A (MA 4)	Low-Code	Low-Code	Pre-Code[2]
Zone 1 (MA 2/3)	Low-Code	Pre-Code[2]	Pre-Code[2]
Zone 0 (MA 1)	Pre-Code[2]	Pre-Code[2]	Pre-Code[2]

1. Assume Moderate-Code design for residential wood-frame buildings (W1).
2. Assume Low-Code design for residential wood-frame buildings (W1).

Guidance given in Table 2.2 for selection of an appropriate seismic design level applies to generic building types of Ordinary construction quality. Conceptually, each type of generic building and level of seismic design also includes buildings of Inferior and Superior construction quality, although distinguishing between generic building type on the basis of construction quality is usually impossible (since only the design vintage is typically known). Nonetheless, the *Hazus* provides users with opportunity of selecting from one of nine combinations of seismic design level (High, Moderate and Low) and construction quality (Superior, Moderate and Low). In terms of the amount damage predicted, buildings of Ordinary construction may be approximately related to other combinations of seismic design level and construction quality as shown in Table 2.3.

Table 2.3. Approximate Relationship of Seismic Design Level and Construction Quality

Construction Quality	Seismic Design Level			
	High-Code	Moderate-Code	Low-Code	None
Superior	Special[1]	High-Code	Moderate-Code	Low-Code
Ordinary	High-Code	Moderate-Code	Low-Code	Pre-Code
Inferior	Moderate-Code	Low-Code	Pre-Code	Pre-Code

1. Special High-Code includes essential facilities such as post-1973 California hospitals.

2.4 Structural and Nonstructural Systems and Contents

Buildings are composed of both structural (load carrying) and nonstructural systems (e.g., architectural and mechanical components). While damage to the structural system is the most important measure of building damage affecting casualties and catastrophic loss of function (due to unsafe conditions), damage to nonstructural systems and contents tends to dominate economic loss. Typically, the structural system represents about 25% of the building's worth.

To better estimate different types of loss, building damage functions separately predict damage to: (1) the structural system, (2) drift-sensitive nonstructural components, such as partition walls that are primarily affected by building displacement, and (3) acceleration-sensitive nonstructural components, such as suspended ceilings, that are primarily affected by building shaking. Building contents are also considered to be acceleration sensitive. Distinguishing between drift- and acceleration-sensitive nonstructural components, and contents, permits more realistic estimates of damage considering building response. Table 2.4 lists typical drift-sensitive and acceleration-sensitive components and building components.

Table 2.4. *Hazus* Classification of Drift-Sensitive and Acceleration-Sensitive Nonstructural Components and Building Contents

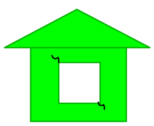
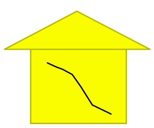
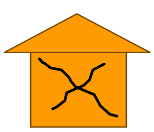
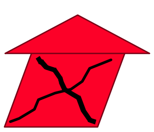
System Type	Component Description	Drift-Sensitive	Acceleration-Sensitive
Architectural	Nonbearing Walls/Partitions	●	
	Cantilever Elements and Parapets		●
	Exterior Wall Panels	●	
	Veneer and Finishes	●	
	Penthouses	●	
	Racks and Cabinets		●
	Access Floors		●
	Appendages and Ornaments		●
Mechanical and Electrical	General Mechanical (boilers, etc.)		●
	Manufacturing and Process Machinery		●
	Piping Systems		●
	Storage Tanks and Spheres		●
	HVAC Systems (chillers, ductwork, etc.)		●
	Elevators		●
	Trussed Towers		●
	General Electrical (switchgear, ducts, etc.)		●
	Lighting Fixtures		●
Contents	File Cabinets, Bookcases, etc.		●
	Office Equipment and Furnishings		●
	Computer/Communication Equipment		●
	Nonpermanent Manufacturing Equipment		●
	Manufacturing/Storage Inventory		●
	Art and Other Valuable Objects		●

2.5 Damage States

Damage states are defined separately for structural and nonstructural systems of a building. Damage is described by one of four discrete damage states: Slight, Moderate, Extensive or Complete, and Collapse as subset of Complete structural damage. Of course, actual building damage varies as a continuous function of earthquake demand. Ranges of damage are used to describe building damage, since it is not practical to have a continuous scale, and damage states provide the user with an understanding of the building's physical condition. Loss functions relate the physical condition of the building to various loss parameters (i.e., direct economic loss, casualties, and loss of function). For example, direct economic loss due to Moderate damage is assumed to correspond to 10% replacement value of structural and nonstructural components, on the average.

The four damage states of the FEMA/NIBS methodology are similar to the damage states defined in *Expected Seismic Performance of Buildings* [EERI, 1994], except that damage descriptions vary for each model building type based on the type of structural system and material. Table 2.5 provides structural damage states for W1 buildings (light frame wood) typical of the conventional construction used for single-family homes.

Table 2.5. Example Damage States - Light-Frame Wood Buildings (W1)

Damage State		Description
	**Slight**	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	**Moderate**	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	**Extensive**	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	**Complete**	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.

2.6 Building Capacity Curves

A building capacity curve is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e., a force-deflection plot). It is derived from a plot of static-equivalent base shear versus building displacement at the roof, known commonly as a pushover curve. In order to facilitate direct comparison with spectral demand, base shear is converted to spectral acceleration, and the roof displacement is converted to spectral displacement using modal properties that represent pushover response. Pushover curves and related-capacity curves, are derived from concepts similar to those of the *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* [FEMA, 1997], and in *Seismic Evaluation and Retrofit of Concrete Buildings* [SSC, 1996], known as *ATC-40*.

Building capacity curves are constructed for each model building type and represent different levels of lateral force design and for a given loading condition, expected building performance. Each curve is defined by two control points: (1) the "yield" capacity, and (2) the "ultimate" capacity. The yield capacity represents the lateral strength of the building and accounts for design strength, redundancies in design, conservatism in code requirements and expected (rather than nominal) strength of materials. Design strengths of model building types are based on the requirements of current model seismic code provisions (e.g., 1994 *UBC* or *NEHRP Provisions*) or on an estimate of lateral strength for buildings not designed for earthquake loads. Certain buildings designed for wind, such as taller buildings located in zones of low or moderate seismicity, may have a lateral design strength considerably greater than those based on seismic code provisions.

The ultimate (plastic) capacity represents the maximum strength of the building when the global structural system has reached a full mechanism. Typically, a building is assumed capable of deforming beyond its ultimate point without loss of stability, but its structural system provides no additional resistance to lateral earthquake force. Up to yield, the building capacity curve is assumed to be linear with stiffness based on an estimate of the expected period of the building. From yield to the ultimate point, the capacity curve transitions in slope from an essentially elastic state to a fully plastic state. The capacity curve is assumed to remain plastic past the ultimate point. An example building capacity curve is shown in Figure 2.3.

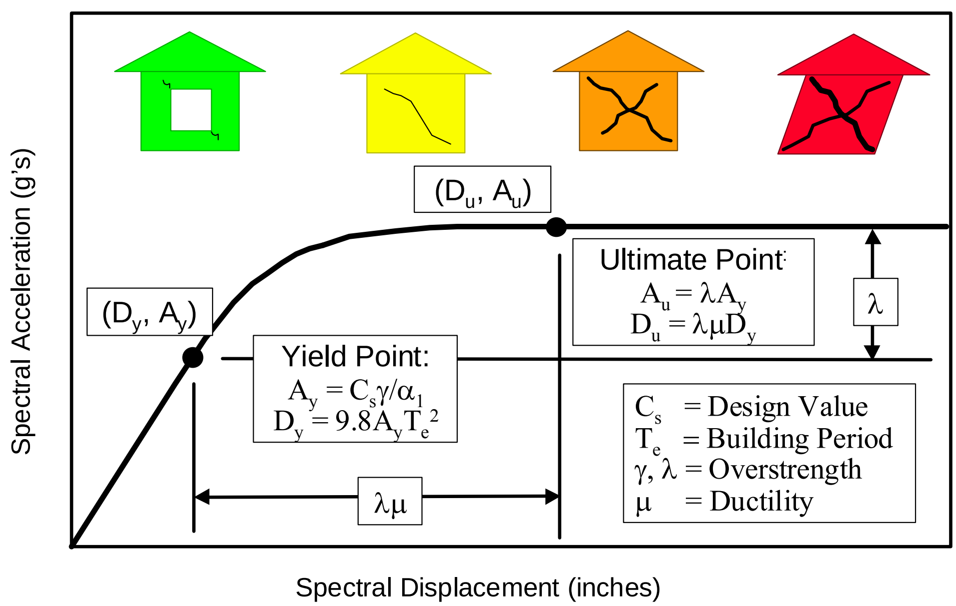


Figure 2.3. Example Building Capacity Curve and Control Points

The following parameters define the yield point and the ultimate point of capacity curves as shown in Figure 2.3:

- C_s point of significant yielding of design strength coefficient (fraction of building's weight),
- T_e expected "elastic" fundamental-mode period of building (seconds),
- α_1 fraction of building weight effective in the pushover mode,
- α_2 fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement (not shown in Figure 2.3),
- γ "overstrength" factor relating "true" yield strength to design strength,
- λ "overstrength" factor relating ultimate strength to yield strength, and
- μ "ductility" ratio relating ultimate displacement to λ times the yield displacement (i.e., assumed point of significant yielding of the structure).

2.7 Building Response Calculation

Building response is determined by the intersection of the demand spectrum and the building capacity curve. Intersections are illustrated in Figure 2.4 for three example demand spectra representing what can be considered as weak, medium and strong ground shaking, and two building capacity curves representing weaker and stronger construction, respectively. As shown in Figure 2.4, stronger and stiffer construction displaces less than weaker and more flexible construction for the same level of spectral demand, and less damage is expected to the structural system and nonstructural components sensitive to drift. In contrast, stronger (and stiffer) construction will shake at higher acceleration levels, and more damage is expected to nonstructural components and contents sensitive to acceleration.

The demand spectrum is based on the 5%-damped response spectrum at the building's site (or center of a study area containing a group of buildings), reduced for effective damping when effective damping exceeds the 5% damping level of the input spectrum. Background on the 5%-damped response spectrum of ground shaking is provided in Section 5.

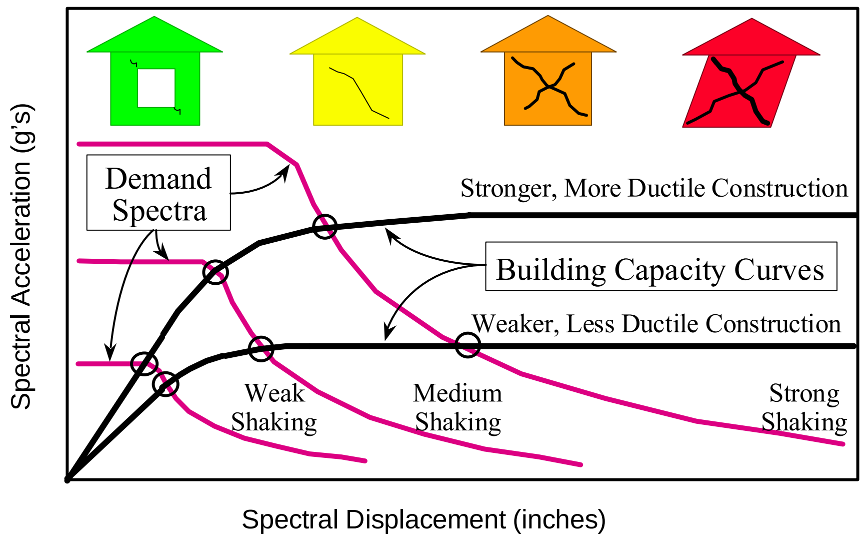


Figure 2.4. Example Intersection of Demand Spectra and Building Capacity Curves

2.8 Building Fragility Curves

Building fragility curves are lognormal functions that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given median estimates of spectral response, for example spectral displacement. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking.

Figure 2.5 provides an example of fragility curves for the four damage states used in the FEMA/NIBS methodology and illustrates differences in damage-state probabilities for three levels of spectral response corresponding to weak, medium, and strong earthquake ground shaking, respectively. The terms "weak," "medium," and "strong" are used here for simplicity; in the actual methodology, only quantitative values of spectral response are used.

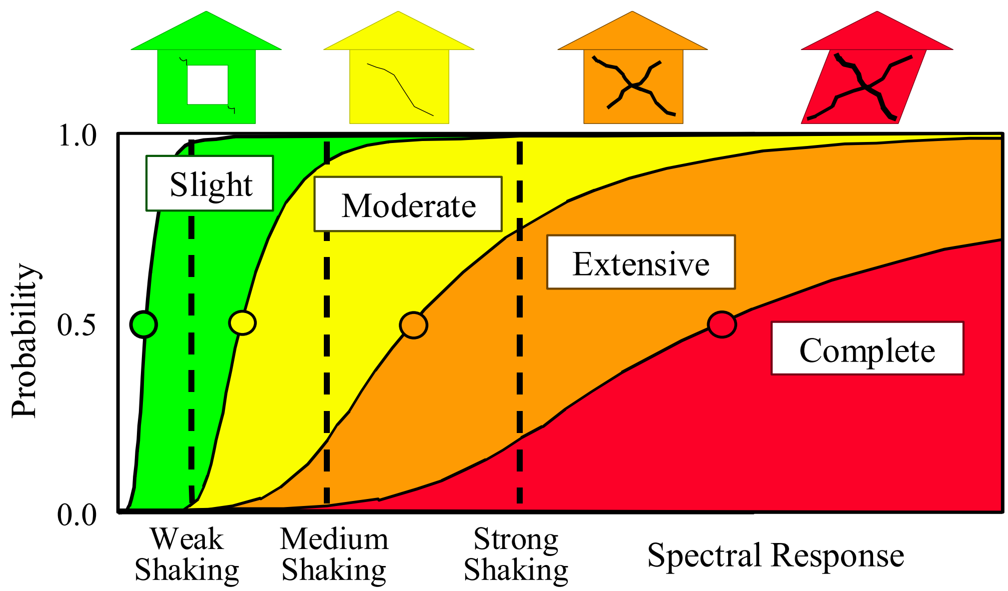


Figure 2.5. Example Fragility Curves for Slight, Moderate, Extensive and Complete Damage

The fragility curves distribute damage among Slight, Moderate, Extensive and Complete damage states. For any given value of spectral response, discrete damage-state probabilities are calculated as the difference of the cumulative probabilities of reaching, or exceeding, successive damage states. The probabilities of a building reaching or exceeding the various damage levels at a given response level sum to 100%. Discrete damage-state probabilities are used as inputs to the calculation of various types of building-related loss. Figure 2.6 provides an example of discrete damage state probabilities for the three levels of earthquake ground shaking.

Each fragility curve is defined by a median value of the demand parameter (e.g., spectral displacement) that corresponds to the threshold of that damage state and by the variability associated with that damage state. For example, the spectral displacement, S_d, that defines the threshold of a particular damage state (ds) is given by Equation (2-1):

$$S_d = \overline{S}_{d,ds}\ \varepsilon_{ds} \qquad (2\text{-}1)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement of damage state, ds,

ε_{ds} is a lognormal random variable with a unit median value and a logarithmic standard deviation, β_{ds}.

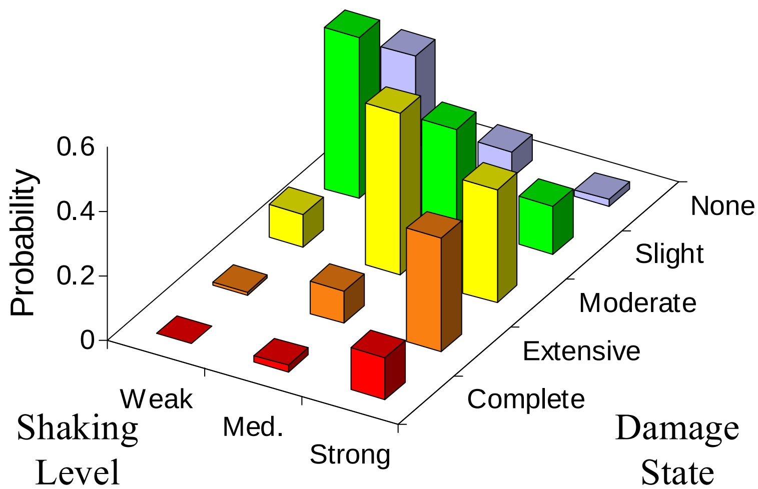


Figure 2.6. Example Damage-State Probabilities for Weak, Medium and Strong Shaking Levels

In a more general formulation of fragility curves, the lognormal standard deviation, β, has been expressed in terms of the randomness and uncertainty components of variability, β_R and β_U, respectively [Kennedy, et. al., 1980]. In this formulation, uncertainty represents the component of the variability that could theoretically be reduced with improved knowledge; whereas, randomness represents the inherent variability (in response) that cannot be eliminated, even with perfect knowledge. Since it is not considered practical to separate uncertainty from randomness, the combined variability, β, is used to develop a composite "best-estimate" fragility curve.

The conditional probability of being in, or exceeding, a particular damage state, ds, given the spectral displacement, S_d, (or other seismic demand parameter) is defined by Equation (2-2):

$$P\left[ds \middle| S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \qquad (2\text{-}2)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage state, ds,

β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state, ds, and

Φ is the standard normal cumulative distribution function.

2.9 Example Capacity and Fragility Data

Figures 2.7 through 2.11 are plots of capacity curves and damage-state medians for light-frame wood, low-rise URM bearing wall, and low-rise, mid-rise and high-rise concrete moment frame buildings, respectively. Below each figure, Tables 2.6 through 2.10 summarize elastic period data and drift ratios corresponding to capacity curve control points and damage-state medians. Each figure (and table) includes capacity and fragility data for different seismic design levels.

Comparison of Figure 2.7 and Table 2.6 data for light-wood frame buildings with Figure 2.8 and Table 2.7 data for low-rise URM bearing wall buildings illustrates capacity curve and fragility properties ranging from the strongest, most "ductile" to the weakest, least "ductile" generic building types. Comparison of data shown in Figures 2.9, 2.10 and 2.11 (and corresponding tables) illustrates the reduction in stiffness and strength of capacity curves (and related changes to damage-state medians) with increase in building height.

2.10 Building Loss Functions

Building loss functions of *Hazus* may be thought of as the second part of an integral two-step process in which estimates of building damage (i.e., probability of damage state) are transformed into estimates of various types of loss.

The building loss functions are numerous and often complex, and a proper description of the background and theory would be too extensive to include in this manual. Users are directed to the *Hazus-MH 2.1 Technical Manual* for complete description of building loss functions. The *Earthquake Spectra* paper "Estimation of Earthquake Losses to Buildings" [Kircher, 1997b] also describes building loss functions used to calculate direct economic loss and compares calculated values with dollar losses of the 1994 Northridge earthquake.

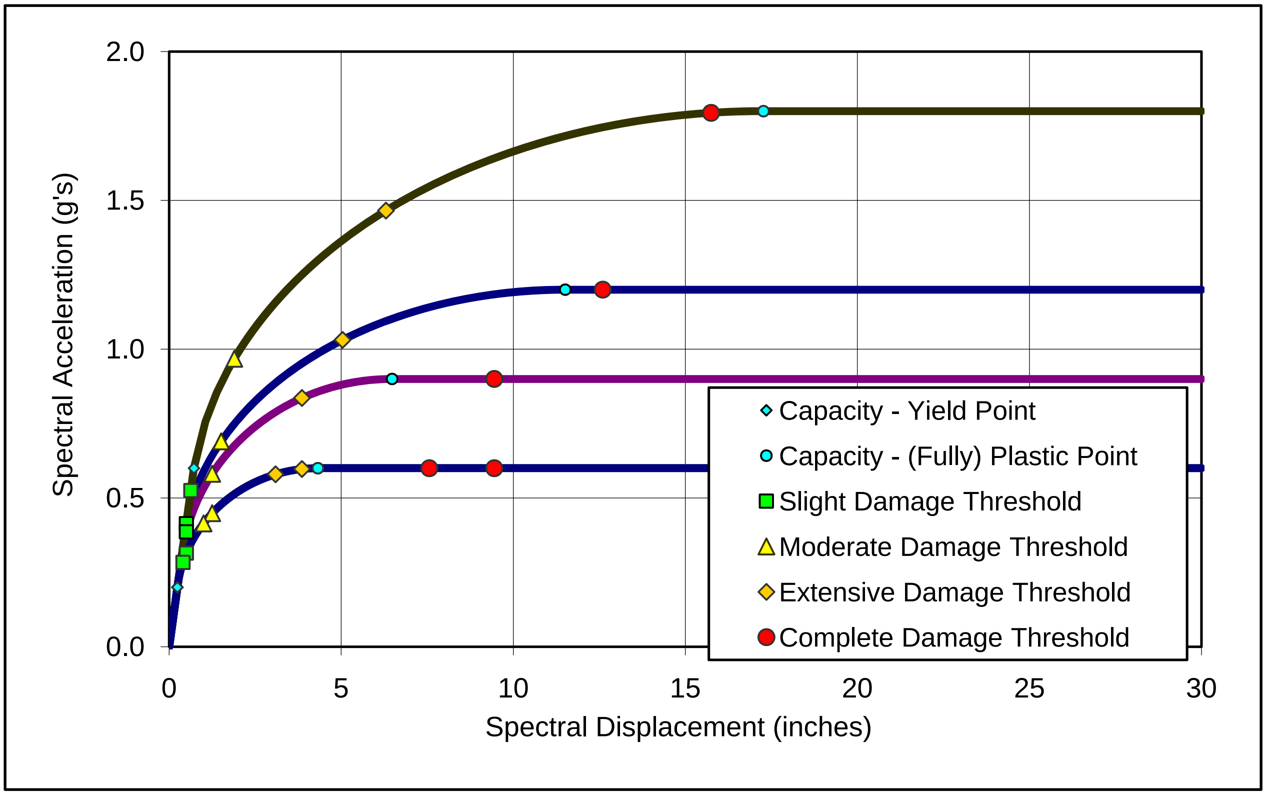


Figure 2.7. Generic Building Type W1 (Light Frame Wood < 5,000 sq. ft.)[1] – Capacity Curves and Structural Damage-State Thresholds (Fragility Medians) for Five Seismic Design Levels (Special High, High, Moderate, Low and Pre-Code)

Table 2.6. Generic Building Type W1 (Light Frame Wood < 5,000 sq. ft.)[1] – Elastic Period Values and Average Inter-Story Drift Ratios of Capacity Curve Control Points and Structural Damage State Thresholds (Fragility Medians)

Seismic Design Level	Elastic Period (sec.)	Average Inter-Story Drift Ratio					
		Capacity Curve Control Points		Structural Damage State Thresholds (Fragility Medians)			
		Yield	Plastic	Slight	Moderate	Extensive	Complete
Special High-Code	0.35	0.0057	0.1371	0.0050	0.0150	0.0500	0.1250
High-Code	0.35	0.0038	0.0913	0.0040	0.0120	0.0400	0.1000
Moderate-Code	0.35	0.0029	0.0514	0.0040	0.0099	0.0306	0.0750
Low Code	0.35	0.0019	0.0343	0.0040	0.0099	0.0306	0.0750
Pre-Code	0.35	0.0019	0.0343	0.0032	0.0079	0.0245	0.0600

1. A typical W1 building is 1-story (i.e., 14 feet) in height. Spectral displacement is equal to 0.75 x roof displacement and base shear is equal to 0.75W x spectral acceleration.

Figure 2.8. Generic Building Type URML (Low-Rise Unreinforced Masonry Bearing Walls)[1] – Capacity Curves and Structural Damage-State Thresholds (Fragility Medians) for the Pre-Code Seismic Design Level

Table 2.7. Generic Building Type URML (Mid-Rise URM Bearing Walls)[1] – Elastic Period Values and Average Inter-Story Drift Ratios of Capacity Curve Control Points and Structural Damage State Thresholds (Fragility Medians)

Seismic Design Level	Elastic Period	Average Inter-Story Drift Ratio					
		Capacity Curve Control Points		Structural Damage State Thresholds (Fragility Medians)			
	(sec.)	Yield	Plastic	Slight	Moderate	Extensive	Complete
Special High-Code	0.35	0.0057	0.1371	0.0050	0.0150	0.0500	0.1250
High-Code	0.35	0.0038	0.0913	0.0040	0.0120	0.0400	0.1000
Moderate-Code	0.35	0.0029	0.0514	0.0040	0.0099	0.0306	0.0750
Low Code	0.35	0.0019	0.0343	0.0040	0.0099	0.0306	0.0750
Pre-Code	0.35	0.0019	0.0343	0.0032	0.0079	0.0245	0.0600

1. A typical URML building is 1-story (i.e., 15 feet) in height. Spectral displacement is equal to 0.75 x roof displacement and base shear is equal to 0.50W x spectral acceleration.

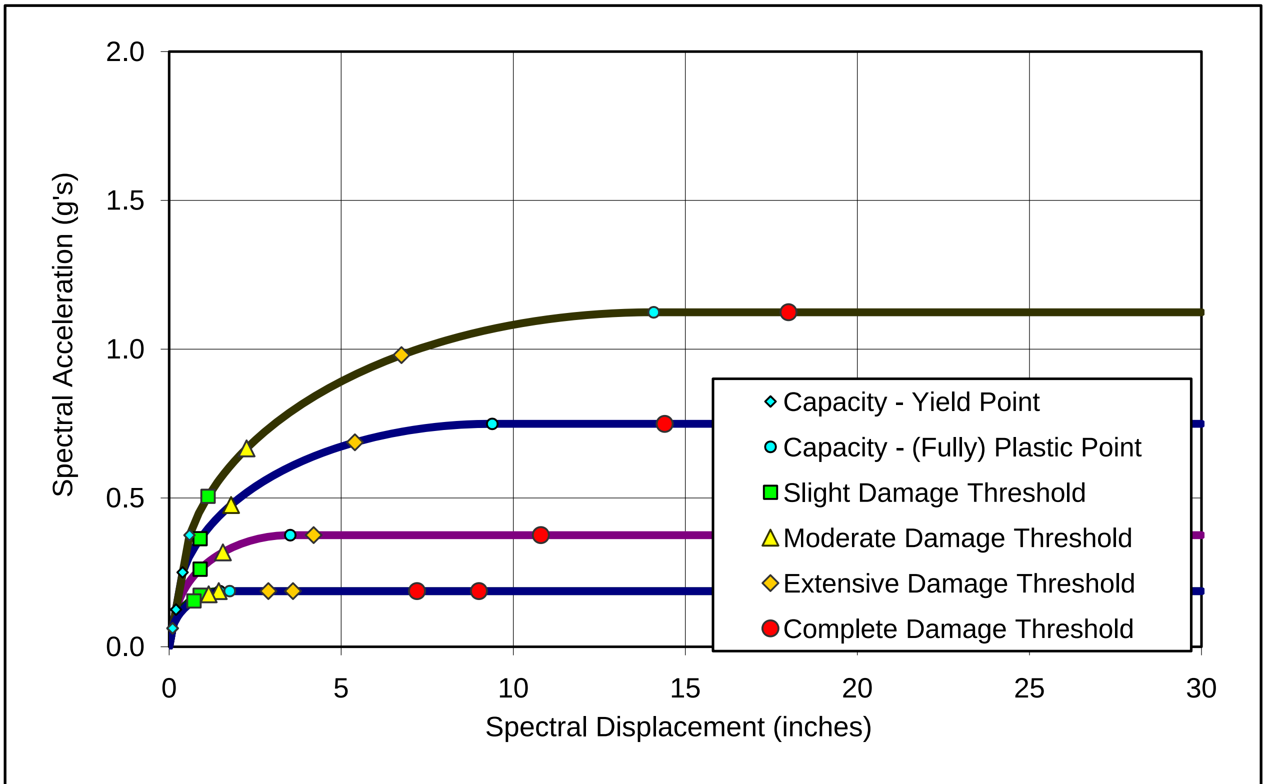


Figure 2.9. Generic Building Type C1L (Low-Rise Concrete Moment Frame)[1] – Capacity Curves and Structural Damage-State Thresholds (Fragility Medians) for Five Seismic Design Levels (Special High, High, Moderate, Low and Pre-Code)

Table 2.8. Generic Building Type C1L (Low-Rise Concrete Moment Frame)[1] – Elastic Period Values and Average Inter-Story Drift Ratios of Capacity Curve Control Points and Structural Damage State Thresholds (Fragility Medians)

Seismic Design Level	Elastic Period (sec.)	Average Inter-Story Drift Ratio					
		Capacity Curve Control Points		Structural Damage State Thresholds (Fragility Medians)			
		Yield	Plastic	Slight	Moderate	Extensive	Complete
Special High-Code	0.40	0.0033	0.0782	0.0063	0.0125	0.0375	0.1000
High-Code	0.40	0.0022	0.0522	0.0050	0.0100	0.0300	0.0800
Moderate-Code	0.40	0.0011	0.0196	0.0050	0.0087	0.0233	0.0600
Low Code	0.41	0.0006	0.0082	0.0050	0.0080	0.0200	0.0500
Pre-Code	0.41	0.0006	0.0098	0.0040	0.0064	0.0160	0.0400

1. A typical C1L building is 2-stories (i.e., 20 feet) in height. Spectral displacement is equal to 0.75 x roof displacement and base shear is equal to 0.80W x spectral acceleration.

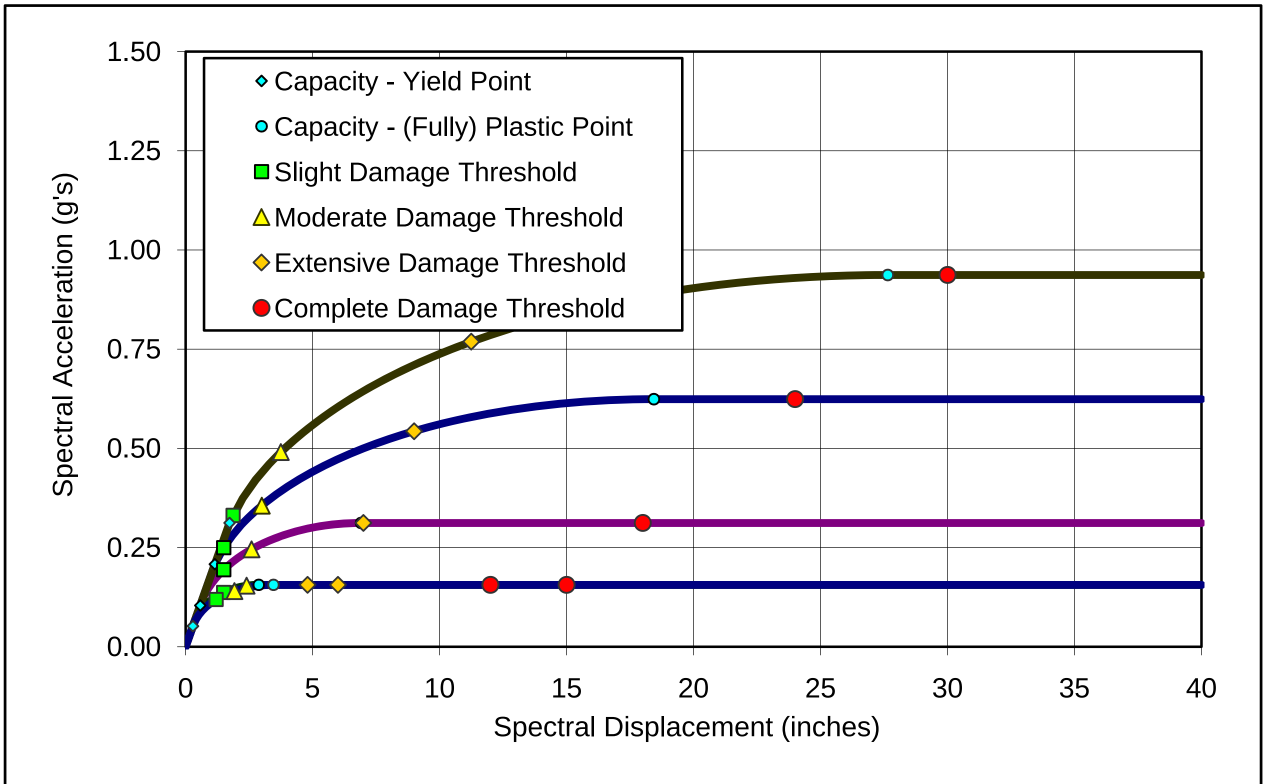


Figure 2.10. Generic Building Type C1M (Mid-Rise Concrete Moment Frame)[1] – Capacity Curves and Structural Damage-State Thresholds (Fragility Medians) for Five Seismic Design Levels (Special High, High, Moderate, Low and Pre-Code)

Table 2.9. Generic Building Type C1M (Mid-Rise Concrete Moment Frame)[1] – Elastic Period Values and Average Inter-Story Drift Ratios of Capacity Curve Control Points and Structural Damage State Thresholds (Fragility Medians)

Seismic Design Level	Elastic Period	Average Inter-Story Drift Ratio					
		Capacity Curve Control Points		Structural Damage State Thresholds (Fragility Medians)			
	(sec.)	Yield	Plastic	Slight	Moderate	Extensive	Complete
Special High-Code	0.75	0.0038	0.0614	0.0042	0.0083	0.0250	0.0667
High-Code	0.75	0.0026	0.0410	0.0033	0.0067	0.0200	0.0533
Moderate-Code	0.76	0.0013	0.0154	0.0033	0.0058	0.0156	0.0400
Low Code	0.76	0.0006	0.0064	0.0033	0.0053	0.0133	0.0333
Pre-Code	0.76	0.0006	0.0077	0.0027	0.0043	0.0107	0.0267

1. A typical C1M building is 5-stories (i.e., 50 feet) in height. Spectral displacement is equal to 0.75 x roof displacement and base shear is equal to 0.80W x spectral acceleration.

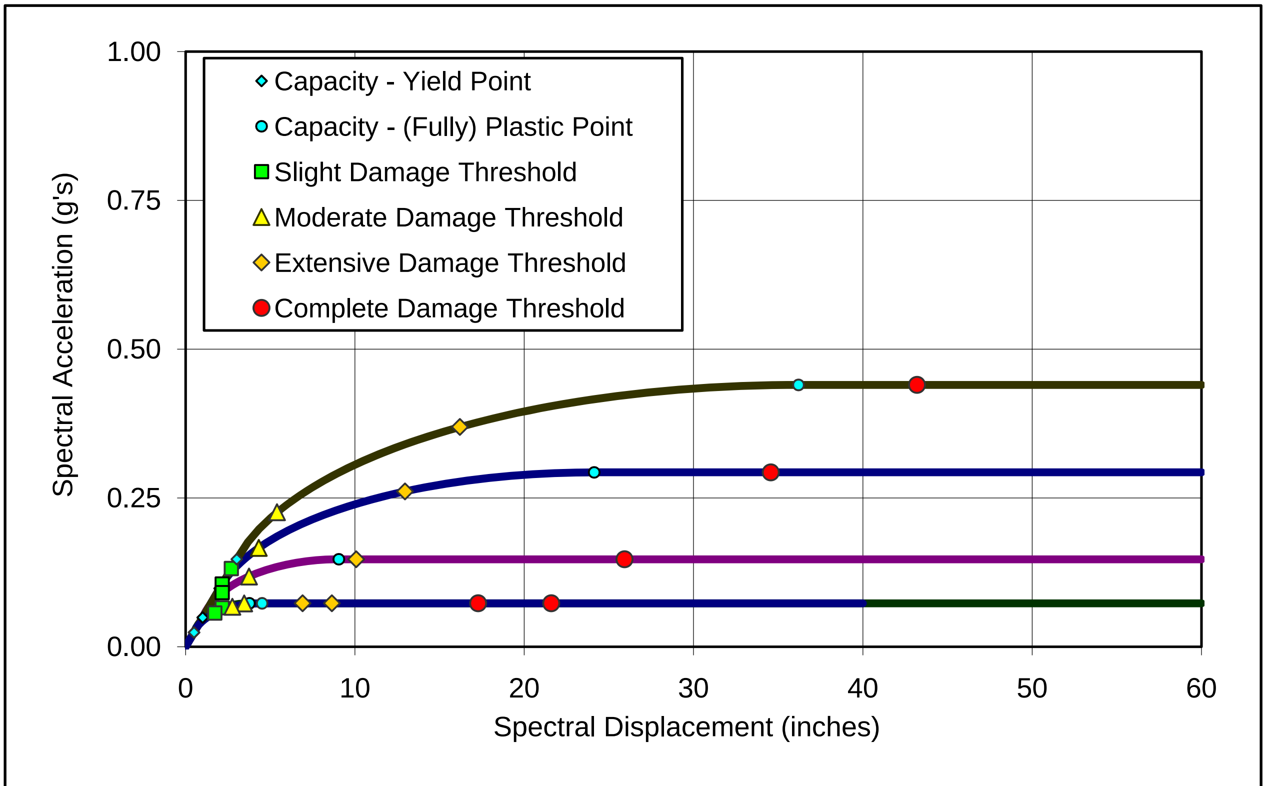


Figure 2.11. Generic Building Type C1H (High-Rise Concrete Moment Frame)[1] – Capacity Curves and Structural Damage-State Thresholds (Fragility Medians) for Five Seismic Design Levels (Special High, High, Moderate, Low and Pre-Code)

Table 2.10. Generic Building Type C1H (High-Rise Concrete Moment Frame)[1] – Elastic Period Values and Average Inter-Story Drift Ratios of Capacity Curve Control Points and Structural Damage State Thresholds (Fragility Medians)

Seismic Design Level	Elastic Period (sec.)	Average Inter-Story Drift Ratio					
		Capacity Curve Control Points		Structural Damage State Thresholds (Fragility Medians)			
		Yield	Plastic	Slight	Moderate	Extensive	Complete
Special High-Code	1.45	0.0035	0.0419	0.0031	0.0063	0.0188	0.0500
High-Code	1.45	0.0023	0.0279	0.0025	0.0050	0.0150	0.0400
Moderate-Code	1.45	0.0012	0.0105	0.0025	0.0043	0.0117	0.0300
Low Code	1.46	0.0006	0.0044	0.0025	0.0040	0.0100	0.0250
Pre-Code	1.46	0.0006	0.0052	0.0020	0.0032	0.0080	0.0200

1. A typical C1H building is 12-stories (i.e., 120 feet) in height. Spectral displacement is equal to 0.60 x roof displacement and base shear is equal to 0.75W x spectral acceleration.

SECTION 3

SUMMARY OF BUILDING-SPECIFIC DATA PROVIDED BY USER

3.1 Introduction

The accuracy of building-specific loss estimates depends primarily on the extent and quality of the information provided by the user (e.g., the seismic/structural engineer). While default data is provided as a starting point and may be used if considered appropriate, the more effort the user puts into the determination of building-specific data, the more reliable the results will be. Conversely, not all input data have the same level of importance in terms of the reliability of the results. This section describes required input data to be provided by the user and indicates, qualitatively, the likely relative importance of the data to loss estimates.

3.2 Site/Source Seismic Hazard Data

Seismic hazard data are not required for development of building damage and loss functions, but are arguably the most important data that will be input by the user for loss estimation. *Hazus* permits users to select the scenario earthquake magnitude, source type and location, and other factors affecting seismic hazard at the building site.

For building-specific loss estimation, it would generally be expected that the user has carefully researched and determined an appropriate scenario earthquake. Typically, this would include identifying source type, magnitude and geographical location of the fault rupture plane for Western United States (WUS) events, or the epicenter for Central and Eastern United States (CEUS) events. It would also be expected that the user has obtained certain geotechnical data including site class (soil type), the susceptibility of the site to either liquefaction or landslide, and a determination that surface fault rupture is not a credible hazard at the site.

Site data on soil type (and ground failure) cannot be input directly to the AEBM, but can be input to the *Hazus* software as soil or ground failure data maps or by modifying default data on a census tract-by-census basis. If the user provides no information, the AEBM will calculate damage and loss based on ground shaking corresponding to the default soil type (i.e., Soil Class D) and will ignore the effects of ground failure. Section 9.2.7 of *the Hazus-MH 2.1 User's Manual* describes how users may include site conditions (other than Soil Class D) and effects of ground failure in *Hazus* analyses. Users would need to make changes to default soil type (and ground failure data) prior to running the AEBM.

3.3 Inventory Data

It is expected that the user will have basic (inventory) data on each AEBM building (or group of buildings) of interest, including building location, size, occupancy, replacement value and other financial data. In general, these data are known by building owners or are otherwise available to users performing detailed building-specific analyses. For individual buildings, inventory data include the following:

Building Location – What is the geographical location of the building (e.g., address and latitude/longitudinal coordinates of site)?

Building Occupants – How many people use the building during the day and at night? What percentage of the building is owner occupied?

Building Size – What is the gross square footage, the number of floors and height of the building?

Replacement Value – What is the replacement value of the building, contents (and/or business inventory)?

Loss of Function Cost – What are the financial data and costs associated with loss of building function, including business income, wages paid, and relocation costs due to disruption of operation and rental of temporary space?

Users must provide inventory data to run the AEBM. In contrast, performance data that define building response properties, capacity curves and fragility (damage) functions, and loss data described in the following sections may be based entirely on default values of *Hazus* parameters.

The AEBM develops an initial "profile" of building response, damage and loss parameters based on default values of *Hazus* corresponding to the (1) occupancy class, (2) building type, (3) seismic design level and (4) building quality of the building (or group of buildings) of interest. As a minimum, users must provide these four building characteristics to run the AEBM. These characteristics can be very important to AEBM estimates of damage and loss, if default values are not modified to incorporate building-specific data.

3.4 Performance Data

Data describing the expected performance of the structural system and nonstructural components are required to develop improved building-specific damage functions. These data include an improved understanding of the structure's response properties and damage to components and elements as a function of the amplitude of response. These data are best determined from a pushover analysis of the building using procedures of the *FEMA Guidelines* or the *Seismic Evaluation and Retrofit of Concrete Buildings (ATC-40)*. It is expected that users are familiar with these documents and will perform a pushover analysis to determine input data.

3.4.1 Building Failure Modes

The single most important benefit of pushover analysis is an improved understanding of the failure mode(s) of the building due to ground shaking. The user is expected to be familiar with the building type (i.e., structural system), knowledgeable regarding the type of damage that has occurred to similar structures in past earthquakes, and capable of developing and analyzing representative models. While pushover analysis will produce detailed information on the performance of elements and components, the results are valid only if elements and components are modeled in a realistic and appropriate manner. Models need not be overly complex, but must capture the important characteristics of plausible modes of failure.

Pushover analyses typically assume the building is free to displace laterally. Adjacent buildings or other structures are often close and would prevent free movement. In such cases, the pushover analysis would not capture "pounding" effects (unless the pushover model was developed with gap elements, etc.).

On a more general basis, pushover analysis is limited to evaluating peak building response due to ground shaking. In general, ground shaking controls damage and loss estimates. However, at sites with high or very high susceptibility to liquefaction or landslide, ground failure can dominate the calculation of loss. In such cases, developing detailed pushover models would not significantly improve the accuracy of damage and loss estimates. Likewise, pushover analysis does not address other non-shaking failure modes, such as those due to inundation, fire, and hazardous materials release.

Pushover analysis necessarily focuses on structural failure modes. Nonstructural components and contents can play a dominant role in building losses. For example, does the building have particularly vulnerable or hazardous nonstructural systems or components (e.g., hollow clay tile partition walls) or particularly vulnerable or hazardous contents (e.g., large quantity of hazardous of flammable material)? Building surveys and evaluations of nonstructural components and contents may be used to identify hazardous nonstructural components and contents.

3.4.2 Pushover Models and Modal Properties

Hazus methods estimate building damage based on inter-story drift and floor acceleration. It is important that pushover models incorporate a sufficient number of elements/components to accurately capture inter-story drift and floor acceleration. Foundation and/or diaphragm flexibility should also be modeled, if such behavior would significantly influenced performance of elements and components.

For buildings with complex configurations or which are susceptible to torsion, pushover models would need to be 3-dimensional (with push force applied on principle axes), or otherwise need to account for building rotation. Pushover curves should be developed for each direction of response (with unique response properties) of each structural segment (if the building has more than one segment) of the building. Each pushover curve should incorporate the flexibility of all elements and components that contribute significantly to building response.

Pushover curves (as used in the *NEHRP Guidelines* and *ATC-40*) represent roof displacement vs. base shear. Typically, these curves are calculated up to the "performance point" which is based on some specified level of seismic demand. *Hazus* methods estimate response (damage and loss) for an arbitrary level of shaking and therefore require building capacity information at all possible displacements. Pushover curves should be calculated at displacements up to complete failure of the structural system. *Hazus* methods estimate spectral response using the capacity spectrum method. Capacity curves are derived from pushover curves using the shape of pushover mode, and the distribution of mass throughout the building. Pushover mode shape (and mass distribution throughout the building) data should be calculated for each pushover curve.

3.4.3 Element/Component Response Characteristics

Hazus methods estimate building damage based on threshold values of inter-story drift (and floor acceleration) that initiate different states of damage (e.g., Slight, Moderate, Extensive and Complete). These threshold values of damage states represent generic building types and are not necessarily appropriate for a specific building. In particular, buildings with certain types of irregularities or vulnerable configurations could have significantly lower damage-state thresholds. Values of inter-story drift defining structural damage states should be selected considering irregularities (e.g., soft story), brittle failure of elements an components and other factors that influence the performance of the structural system.

The results of pushover analysis of a specific building provide a much better understanding of the behavior (performance) of elements/components. It is expected that users will perform pushover analysis in accordance with the nonlinear static analysis procedures of the *NEHRP Guidelines* (or *ATC-40*) and relate the performance of elements/components to various levels of earthquake response (e.g., building drift). This manual guides users in the determination of appropriate threshold values of damage states (and loss functions) based on this information. This is both the most important and most subjective aspect of incorporating pushover analysis results into *Hazus* loss estimation.

3.5 Loss Data

Data on occupants, the financial value of the building and its operation (including costs of repairs) and the time required to make repairs are required to develop improved building-specific loss functions. *Hazus* loss functions are typically based on the specific or general occupancy (use) of the building, and building occupancy is mapped to model building type on a census-tract basis in regional loss studies. On an individual building basis, loss functions can be greatly improved by the use of building-specific data.

Loss data may be divided into two groups: occupant data related to the calculation of injuries and deaths, and financial and loss of function data related to calculation of direct economic losses. A possible third data group, related to direct social losses resulting from displaced households and short-term shelter needs, is not included in the methods since building-specific data could not be used to improve the estimates of these types of losses.

3.5.1 Occupant Data

Hazus methods provide estimates of casualties at 2:00 a.m. (nighttime building population), 2:00 p.m. (daytime building population) and 5:00 p.m. (large commuting population). The latter is not included in building-specific methods. Daytime (or nighttime) building population is based on basic building use (e.g., residential, commercial or industrial) and building inventory and census data that distributes the population of the study region among the three basic building use groups (and the fraction assumed to be commuting). *Hazus* does not distribute daytime or nighttime populations (of a study region) to individual buildings.

The user will need to provide the number of daytime and nighttime occupants of individual buildings of the AEBM. The user should also determine if the distribution of the building population is significantly correlated with building failure (e.g., collapse). For example, suppose only a specific portion of a building is determined to be susceptible to collapse. Is this portion of the building densely populated, have an average building population, or perhaps have a very low population (e.g., storage area)?

3.5.2 Financial Data

Hazus estimates direct economic loss to buildings based on separate damage and loss estimates for the structural system, drift-sensitive nonstructural components, acceleration-sensitive nonstructural components, and contents (and business inventory). The repair or replacement cost of each damage state is expressed as a fraction of total replacement cost of the system of interest (i.e., loss ratio). Total building replacement value, including regional adjustment, is distributed between structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive systems. The value of contents is crudely based on a fraction (e.g., 50%) of the building's replacement cost.

The user will need to provide the replacement cost of individual buildings of the AEBM, their contents and business inventories (if applicable). The replacement costs of the last two items can be of particular importance for buildings or businesses that have special (expensive) contents or inventory items (e.g., laboratory or special process equipment). The user should also confirm (or revise accordingly) default values of *Hazus* that distribute replacement cost of the building between structural, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components, respectively.

Hazus relates each damage state to an amount of financial loss as a fraction of replacement value. Users should confirm (or revise accordingly) the default values of *Hazus* parameters that relate damage states to financial loss, considering element/component damage as a function of building drift (e.g., spectral displacement). Users may choose to develop building-specific loss ratios for each damage state that better reflect construction costs associated with inspection, demolition, phasing, unavoidable impact of repair on undamaged systems, etc. Ideally, users would identify damage from pushover analysis, describe the type and extent of repairs required to correct damage, and develop associated repair costs for each damage state.

In addition to repair and replacement costs, direct economic losses also include the financial effects of loss of building function on business income, wage income, relocation and temporary space rental. Users should confirm (or revise accordingly) default values of *Hazus* of the time required for clean-up and repair (construction time), considering the extent of damage determined from pushover analysis and evaluation of damage to building components.

SECTION 4

SUMMARY OF DAMAGE AND LOSS FUNCTION PARAMETERS

4.1 Introduction

This section summarizes the names, definitions and formats (units) of parameters that are used by Advanced Engineering Building Module (AEBM) of the *Hazus-MH 2.1 Software* to define damage and loss functions for buildings. Parameter names and definitions generally follow those used in the *Hazus-MH 2.1 Technical Manual.* Tables and sections of the *Hazus-MH 2.1 Technical* Manual that provide default values of parameters for generic building types are identified for reference by users.

The AEBM has an "Inventory" database and a "Building Characteristics" database. The AEBM Building Characteristics database contains a large number of terms that define damage functions (i.e., response, capacity and fragility parameters) and loss functions (i.e., casualty, direct economic and loss of function parameters). In most cases, these terms are identical with the terms and formulas used by the *Hazus-MH 2.1 Technical Manual* to estimate various types of loss.

While consistent with the underlying methods of *Hazus*, certain terms of AEBM databases are used in formulas to calculate losses that are not fully documented in the *Hazus-MH 2.1 Technical Manual*. In such cases, his section describes the formulas used by the AEBM to calculate losses.

4.2 Damage Functions

Damage function data are contained in the AEBM Building Characteristics database and include capacity curve parameters and response parameters.

4.2.1 Capacity Curve Parameters

Each building has one capacity curve that is defined by two control points, the yield control point and the ultimate control point:

Yield Capacity Control Point: spectral displacement, $\mathbf{D_y}$, in inches, and spectral acceleration, $\mathbf{A_y}$, in units of acceleration (g).

Ultimate Capacity (Plastic) Control Point: spectral displacement, $\mathbf{D_u}$, in inches, and spectral acceleration, $\mathbf{A_u}$, in units of acceleration (g).

Default values of the yield and ultimate capacity control points for each of the 36 (generic) model building types are given in Tables 5.7a through 5.7d of the *Hazus-MH 2.1 Technical Manual* for High-Code, Moderate-Code, Low-Code and Pre-Code seismic design levels, respectively.

4.2.2 Response Parameters

Peak displacement building response is defined by the intersection of demand spectrum (of the scenario earthquake of interest) and the capacity curve. The demand spectrum is the 5%-damped spectrum of ground shaking at the building site reduced for effective damping above 5% of critical. Two parameters, the elastic pre-yield damping and the degradation of post-yield hysteretic response, influence the amount of damping reduction:

Elastic Damping, B_E, expressed as a percentage of critical damping.

Degradation (Kappa) Factors, κ_S, κ_M, κ_L, expressed as a fraction of non-degraded hysteretic behavior for Short, Medium and Long shaking duration.

Values of elastic damping range from 5% of critical for most steel structures to 15% of critical for wood structures (with nailed joints) and generally follow the recommendations of Table 3 of *Earthquake Spectra and Design* [Newmark & Hall, 1982] for materials at or just below yield. Values of the degradation (Kappa) factor are given in Table 5.18 of the *Hazus-MH 2.1 Technical Manual* for each of the 36 (generic) model building types, as a function of the building's seismic design level and the duration of post-yield shaking (i.e., Short, Moderate or Long duration).

Acceleration-sensitive nonstructural components and building contents at upper-floors are influenced by the peak acceleration response of the structure (e.g., capacity curve plateau), while components and contents at lower-floors are influenced more by ground shaking (i.e., peak ground acceleration). Acceleration demand on nonstructural (acceleration-sensitive) components and contents is based on a weighted combination of the fraction of components/contents at the base of the building with those components/contents located at upper-floors.

Nonstructural Fraction (F_{NS}) of acceleration-sensitive nonstructural components (and contents) at lower-floors varies as a function of building height and is assumed to be 0.5 for low-rise buildings, 0.33 for mid-rise buildings and 0.2 for high-rise buildings.

4.2.3 Fragility Curve Parameters

A total of twelve fragility curves describe the probabilities of reaching or exceeding the four discrete damage states (i.e., Minor, Moderate, Extensive and Complete) of the structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive systems, respectively, given a particular level of building response. There are two parameters, the median value of the probability function (assumed to be log-normally distributed) and the lognormal standard deviation value of the distribution, that define each fragility curve:

Damage-State Median spectral displacement, $S_{d,ds}$, in inches, of each structural and nonstructural drift-sensitive damage state, or median spectral acceleration, $S_{a,ds}$, in units of acceleration (g), of each nonstructural acceleration-sensitive damage state.

Damage-State (Beta) Lognormal Standard Deviation, β_{ds}, of each structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive damage state.

Median and Beta values defining structural damage states of each of the 36 (generic) model building types are given in Tables 5.9a through 5.9d of the *Hazus-MH 2.1 Technical Manual* for High-Code, Moderate-Code, Low-Code and Pre-Code seismic design levels, respectively. Median and Beta values defining nonstructural drift-sensitive damage states of each of the 36 (generic) model building types are given in Tables 5.11a through 5.11d of the *Hazus-MH 2.1 Technical Manual* for High-Code, Moderate-Code, Low-Code and Pre-Code (No) seismic design levels, respectively. Median and Beta values defining nonstructural acceleration-sensitive damage states of each of the 36 (generic) model building types are given in Tables 5.13a through 5.13d of the *Hazus-MH 2.1 Technical Manual* for High-Code, Moderate-Code, Low-Code and Pre-Code seismic design levels, respectively.

4.3 Loss Functions

Loss function data are contained in the AEBM Building Characteristics database (i.e., cells 39 – 93 of AEBMBP.DBF) and in the AEBM Inventory database (i.e., cells 10 – 20 of AEBM.DBF). Loss function data include casualty rates, direct economic loss parameters related to damage repair and loss of function factors. The Inventory database defines certain basic building data that are used with other factors to estimate losses, as described below.

4.3.1 Inventory Data

Number of Daytime Occupants, N_{DO}, and **Nighttime Occupants,** N_{NO}, are used in the calculation of the number of expected casualties following the logic described in Section 13.2.1 of the *Hazus-MH 2.1 Technical Manual* (for each Casualty Severity Level). Table 13.2 of the *Hazus-MH 2.1 Technical Manual* provides guidance for estimating the fraction of all occupants likely to be in the building during the day and during the night.

The logic of Section 13.2.1 involves numerous combinations of structural damage and casualty severity levels. However, serious injuries and fatalities tend to be dominated by only a few combinations of Complete structural damage for which the building has also sustained some degree of collapse. The following equations illustrate the calculation of daytime casualties due to full building collapse:

$$SL\_ENDO_i = N_{DO} * P[S_i|COL] * P[COL|PSTR_5] * PSTR_5$$

where:	SL_ENDO_i =	Expected number of daytime casualties of Severity Level i
	$P[S_i|COL]$ =	Probability of Severity Level i given full building collapse
	$P[COL|STR_5]$ =	Probability of full building collapse given Complete structural damage (STR_5)
	$PSTR_5$ =	Probability of Complete structural damage

N_{DO} = Number of daytime occupants of the building.

Total Floor Area, FA, (in square feet) is not used directly in the AEBM but provides a basis to relate building-specific estimates of economic loss to the corresponding methods of the *Hazus-MH 2.1 Technical Manual* for generic building types.

Replacement Value (in dollars) of the building**, RV_B,** is used in calculations of direct economic loss due to the repair (or replacement) of the structural system, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components, respectively:

$$EL\_STR = FV_{STR} * RV_B * \sum_{ds=2}^{5} \left(PSTR_{ds} * STRD_{ds}\right)$$

$$EL\_NSD = FV_{NSD} * RV_B * \sum_{ds=2}^{5} \left(PNSD_{ds} * NSDD_{ds}\right)$$

$$EL\_NSA = (1 - FV_{STR} - FV_{NSD}) * RV_B * \sum_{ds=2}^{5} \left(PNSA_{ds} * NSAD_{ds}\right)$$

where: EL_STR = Loss due to repair of the structural system (dollars)

EL_NSD = Loss due to repair of nonstructural drift-sensitive components (dollars)

EL_NSA = Loss due to repair of nonstructural acceleration-sensitive components (dollars)

$PSTR_{ds}$ = Probability of building being in structural damage state, ds

$PNSD_{ds}$ = Probability of building being in nonstructural drift-sensitive damage state, ds

$PNSA_{ds}$ = Probability of building being in nonstructural acceleration-sensitive damage state, ds

$STRD_{ds}$ = Structural system repair cost of damage state, ds, expressed as a fraction of the total cost of the structural system

$NSDD_{ds}$ = Nonstructural repair cost of damage state, ds, expressed as a fraction of the total cost of nonstructural drift-sensitive components

$NSAD_{ds}$ = Nonstructural repair cost of damage state, ds, expressed as a fraction of the total cost of nonstructural acceleration-sensitive components

FV_{STR} = Fraction of total building replacement value, RV_B, associated with the structural system

FV_{NSD} = Fraction of the fraction of total building replacement value, RV_B, associated with nonstructural drift-sensitive components

RV_B = Replacement value of building (dollars).

The **Replacement Value** of the building, **RV_B,** may be estimated as the product of the **Total Floor Area, FA**, and the total cost per square foot of structural and nonstructural systems.

Appendices 15A and 15C of the *Hazus-MH 2.1 Technical Manual* provide background on the derivation of regional per square foot costs for various occupancies using *Means* data.

Replacement Value (in dollars) of contents, $\mathbf{RV_C}$, and business inventory, $\mathbf{RV_{INC}}$, are used in calculations of direct economic loss due to the replacement of these contents or inventory:

$$EL\_CCD = RV_C * \sum_{ds=2}^{5} \left(PNSA_{ds} * CD_{ds}\right)$$

$$EL\_INV = RV_{INV} * \sum_{ds=2}^{5} \left(PNSA_{ds} * INVD_{ds}\right)$$

where:

EL_CCD =	Loss due to replacement of damaged contents (dollars)
EL_INV =	Loss due to replacement of business inventory (dollars)
$PNSA_{ds}$ =	Probability of building being in nonstructural acceleration-sensitive damage state, ds
CD_{ds} =	Contents replacement cost of damage state, ds, expressed as a fraction of the total cost of contents
$INVD_{ds}$ =	Business inventory replacement cost of damage state, ds, expressed as a fraction of the total cost of nonstructural drift-sensitive components
RV_C =	Replacement value of building contents (dollars)
RV_{INV} =	Replacement value of business inventory (dollars).

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Default replacement values of contents, CV, expressed as a fraction of the **Replacement Value** of the building, $\mathbf{RV_B}$, are provided in Table 15.5 of the *Hazus-MH 2.1 Technical Manual* for various building occupancies. Default replacement values of business inventory are based on the size of the building, the level of annual gross sales and the type of business, as described in Section 15.2.3 of the *Hazus-MH 2.1 Technical Manual.*

Business Income, BINC, by building occupants (dollars per day) is used by the AEBM in the calculation of loss of business income:

$$EL\_INC = (1 - RFBI) * BINC * \sum_{ds=1}^{5} \left(PSTR_{ds} * LOF_{ds}\right)$$

where:

EL_INC =	Loss of business income (dollars)
$PSTR_{ds}$ =	Probability of building being in structural damage state, ds
LOF_{ds} =	Loss of function for damage state ds (days)
BINC =	Business income for building occupants (dollars/day)
RFBI =	Recapture factor for loss of business income.

Wages Paid, WAGE, by building occupants (dollars per day) is used by the AEBM in the calculation of loss of wages:

$$EL\_WAGE = (1 - RFW) * WAGE * \sum_{ds=1}^{5} (PSTR_{ds} * LOF_{ds})$$

where:
- EL_WAGE = Loss of wages (dollars)
- $PSTR_{ds}$ = Probability of building being in structural damage state, ds
- LOF_{ds} = Loss of function for damage state ds (days)
- WAGE = Wages paid by building occupants (dollars/day)
- RFW = Recapture factor for loss of wages.

Section 15.2.6.1 of the *Hazus-MH 2.1 Technical Manual* provides default values of wage and business income recapture factors based on building occupancy type.

Disruption Cost, DISC, (dollars), **Rental Cost, RENT,** (dollars per day) and percentage of the building that is **Owner Occupied, OO**, are used by the AEBM in the calculation of losses due business relocation and rental income:

$$EL\_REL = DISC * \sum_{ds=3}^{5} PSTR_{ds} + OO * RENT * \sum_{ds=3}^{5} (PSTR_{ds} * RT_{ds})$$

$$EL\_RENT = (1 - OO) * RENT * \sum_{ds=3}^{5} (PSTR_{ds} * RT_{ds})$$

where:
- EL_REL = Loss due to business relocation expenses (dollars)
- EL_RENT = Loss due to rental of temporary space (dollars)
- $PSTR_{ds}$ = Probability of building being in structural damage state, ds
- RT_{ds} = Recovery time for damage state ds (days)
- RENT = Rental costs for replacement space (dollars/day)
- DISC = Disruption "lump sum" relocation cost (dollars)
- OO = Percentage of building occupied by the owner.

Table 15.13 of the *Hazus-MH 2.1 Technical Manual* provides default values of rental and disruption costs (per square foot) as a function based on building occupancy type

4.3.2 Casualty Rates

Sixteen **Casualty Rates** specify Severity 1, Severity 2, Severity 3 or Severity 4 casualties as a fraction of building occupants for each state of structural damage, assuming that the building has not collapsed. In general, these rates do not govern the estimates of serious injuries and fatalities, which are primarily a function of building collapse. Users are encouraged to use (without modification) the casualty rates given in Tables 13.3 through 13.6 of the *Hazus-MH 2.1 Technical Manual* for the generic building type that is the most similar to the specific building of interest.

Collapse Casualty Rates, **$P[S_i|COL]$** specify the fractions of building occupants expected to be Severity 1, Severity 2, Severity 3 or Severity 4 casualties, respectively, given that Complete structural damage <u>and</u> Collapse has occurred.

The **Collapse Factor, $P[COL|STR_5]$**, specifies the probability of full building collapse given Complete structural damage has occurred, or weighted combination of the probabilities of multiple modes of collapse for which the weighting factor is proportional to the fraction of the building population exposed to collapse. The probability of collapse (given Complete structural damage) may also be thought of as the effective fraction (or ratio) of the building that has collapsed such that when multiplied by total building population the result is expected number of building occupants exposed to life-threatening collapse.

Default values of collapse casualty rates are specified in Table 13.7 of the *Hazus-MH 2.1 Technical Manual* for each casualty severity level as a function of model building type. Default values of the collapse factor are specified in Table 13.8 of the *Hazus-MH 2.1 Technical Manual* as a function of model building type.

Chapter 13 of the *Hazus-MH 2.1 Technical Manual* distinguishes between "indoor" and "outdoor" casualties, the later referring to deaths and injuries to pedestrians (or people in cars, etc.) that are near the building at the time of the earthquake. Tables 13.5 through 13.7 of the *Hazus-MH 2.1 Technical Manual* specify "indoor" casualty rates that are used by the AEBM to estimate building-specific casualties. The AEBM does not calculate "outdoor" casualties.

4.3.3. Repair Cost Rates – Loss Ratios

Twelve **Loss Ratios** specify the fractions of the total cost of the structural system, **$STRD_{ds}$**, the fractions of the total cost of nonstructural drift-sensitive components, **$NSDD_{ds}$**, and the fractions of the total cost of nonstructural acceleration-sensitive components, **$NSAD_{ds}$**, respectively, associated with repair of each damage state, ds.

Repair costs (in dollars per square foot) are the multiplication of loss ratios times the total cost per square foot of the system of interest. Default values of structural repair costs are given in Tables 15.2a through 15.2d of the *Hazus-MH 2.1 Technical Manual* for each damage state, respectively, as a function of building occupancy and model building type. Default values of nonstructural acceleration-sensitive and nonstructural drift-sensitive repair costs are given in Tables 15.3 and 15.4, respectively, of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type. Default repair costs include regional cost modifiers that adjust repair costs based on the building's geographical location.

The **Fractional Value, FV_{STR}**, is the fraction of the total replacement value of the building, **RV_B**, associated with the value of the structural system. The **Fractional Value, FV_{NSD}**, is the fraction of the total replacement value of the building, **RV_B**, associated with the value of nonstructural systems sensitive to drift. The balance of the total replacement value of the building, $\mathbf{RV_B}$, is associated with the value of nonstructural systems sensitive to acceleration.

Four **Loss Ratios** specify fractions of the total cost of contents, $\mathbf{CD_{ds}}$, associated with each damage state, ds. Default values of content loss ratios, CD, are given in Table 15.6 of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type.

Four **Loss Ratios** specify fractions of the total cost of business inventory, $\mathbf{INV_{ds}}$, associated with each damage state, ds. Default values of business inventory loss ratio, INV, are given in Table 15.6 of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type.

4.3.4 Loss of Function and Recovery Time

Building repair time is the time in days required for clean up and construction to repair or replace damage to structural and nonstructural systems. Default values of building repair time, BRT are given in Table 15.10 of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type.

Building Recovery Time, $\mathbf{BCT_{ds}}$, (in days) is the time required to make repairs of each structural damage state, ds, including additional time due to delays in decision-making, financing, inspection, etc. Default values of **Building Recovery Time** are given in Table 15.11 of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type.

Loss of Function, $\mathbf{LOF_{ds}}$, (in days) is the time that the facility is not capable of conducting business and is typically less than repair time due to temporary solutions such as the use of alternative space, etc. Building and service interruption time multipliers may be used to assess **Loss of Function** as a fraction of **Building Recovery Time**. Service interruption multipliers, MOD, are given in Table 15.12 of the *Hazus-MH 2.1 Technical Manual* for each damage state as a function of building occupancy type.

Recapture Factors for business income, **RFBI**, and wages, **RFW**, account for a portion of business income and wage losses (due to loss of function) that are recouped by working overtime, etc. Default values of **Recapture Factors** are given in Section 15.2.6.1 *HAZUS-MH MR5 Technical Manual* as a function of building occupancy type.

SECTION 5

DEVELOPMENT OF CAPACITY CURVES AND RESPONSE PARAMETERS

5.1 Building Model and Pushover Criteria

This section guides users in the development capacity curves and related parameters that are used by Advanced Engineering Building Module (AEBM) to calculate building response as a function of ground shaking at the building site. It is assumed that the user has already performed nonlinear static (pushover) analysis of the building that conforms essentially to the methods of *NEHRP Guidelines* (or *ATC-40*) and to certain other criteria as set forth in this section.

The pushover analysis must appropriately represent the force-deflection and response characteristics of the building of interest. For use in developing fragility functions, the pushover analysis must also appropriately capture the damage patterns of elements and components of the building (as described in the next section). In general, the latter requires more detailed and complex analysis than that required simply for evaluation of building response.

The *NEHRP Guidelines* (and *ATC-40*) provide users with a fairly complete description of the nonlinear static (pushover) method of analysis, including guidance on modeling and evaluation post-yield behavior of elements and components. Additional guidance is provided in this section for performing pushover analysis and using the results in loss estimation studies. Since the *NEHRP Guidelines* (and *ATC-40*) are design documents, the user should be aware that they intentionally (or unintentionally) include some conservatism that is not appropriate for loss estimation. For loss estimation, as compared to design procedures and building code rules, pushover analysis methods and models should fairly represent building (building group) without conservative bias. Building geometry, material strengths and response limits, etc. should all represent typical building conditions and likely response behavior, rather than being based on conservative or “worst-case” assumptions.

Users must determine how many different pushover models are required for loss estimation. For complex buildings, a model could be developed for each horizontal direction of response (if response is different in different directions) and for separate structural segments of the building. It is common for large buildings (in plan) to be composed of more than one structure, separated by construction joints. Each structure can have different capacity and response properties (and fragility and loss functions). For simple symmetrical buildings, a single pushover model would likely be sufficient to represent building behavior. If a single pushover model is used to evaluate a complex and/or irregular building, then the model would need to represent those modes of response and failure that are most likely to occur and cause damage and loss.

Consider, for example, a large tilt-up building, composed of three structural segments in a line (three by one rectangle in plan). Such buildings are commonly used for industrial manufacturing and warehousing facilities. The segments at each end are similar and have tilt-up panels of three sides. The segment in the middle is structurally different and has panels on only two opposing sides of the building. All three segments are strong in the plane of the tilt-up panels near the building’s perimeter, but generally weak in the direction perpendicular to the panels away from building corners. All three segments have flexible diaphragms. Possible building response and failure modes include the following (there may be others):

- Local, out-of-plane failure of some tilt-up planes (due to failure of panel-to-roof connections) accentuated by diaphragm flexibility – most likely to occur at mid-span locations (away from building corners)
- Full collapse of center section in weak direction (perpendicular to tilt-up panels)
- Partial collapse of end sections in the weak direction (near joints with center section) accentuated by torsion response.

The user would likely develop multiple pushover models to evaluate the different modes of response and failure of the building, described above. Multiple pushover analyses could be converted into multiple building damage and loss models (one model per building segment) or folded into a single building damage and loss model. If multiple models of different building segments are developed, then damage and loss would be calculated separately for each and aggregated for the building as a whole.

Developing a single building damage and loss model (e.g., a single capacity curve) for a complex building requires users to judge the mode of failure, direction of response, etc., that best represents the most likely source of earthquake damage and loss. Sections 5.2 and 5.3 assume that the user has resolved building complexity and describe methods for converting a single pushover curve into capacity and response parameters that are compatible with the AEBM.

Users must determine how many and to what degree elements and components are required to be explicitly modeled in pushover analyses used for loss estimation. Fragility concerns (next section) usually control this issue, although modeling of building elements and components is also important to building capacity. For determining capacity curve properties, it is necessary that the pushover mode shape include all elements and components whose individual stiffness (flexibility) significantly affects global building response. From a dynamics standpoint, this requirement may also be thought of as including all "degrees of freedom" that significantly influence dynamic response of the 1st-mode of the building in the direction of interest.

Flexibility of the foundation, floor diaphragms, etc., should be explicitly modeled in the pushover analysis if the addition of the flexibility of these element/components to the pushover model would significantly change pushover mode shape and response. Similarly, no structural elements or components should be excluded from the pushover model simply because they are considered to be of secondary, rather than primary, importance to the structural system. Likewise, architectural elements and components that add significant stiffness to the building (e.g., hollow-clay tile used as in-fill partitions) should be modeled in the pushover analysis (and effectively removed from the model as they fail during pushover analysis).

5.2 Development of Capacity Curve Control Points

5.2.1 Conversion of Pushover Curve to Capacity Curve

The first step in developing capacity curve control points is to convert pushover coordinates of base shear force and control point (e.g., roof) displacement to spectral acceleration and displacement, respectively. The coordinate conversion is described somewhat vaguely as Method 2 in the commentary of the *NEHRP Guidelines* and more completely in *ATC-40*, the latter being consistent with *Hazus* format and terminology.

The conversion of pushover to capacity is illustrated in Figure 5.1. An example pushover curve (normalized by the building's weight, W) is converted to capacity using pushover mode factors, α_1 and α_2. Each point on the normalized pushover curve (D_p, A_p) is factored by the pushover mode factors to create a corresponding point on the capacity curve (D_c, A_c). Provided the pushover curve was developed using a push force pattern based on the 1st-mode shape of the building, then the initial (pre-yield) slope of the capacity curve is directly related to the building's elastic (pre-yield) period (T_e) as described by Equation (5-5). Axes are labeled in terms of Spectral Acceleration and Spectral Displacement in Figure 5.1, recognizing that while pushover and capacity curves can have the same units, they are in different coordinate systems.

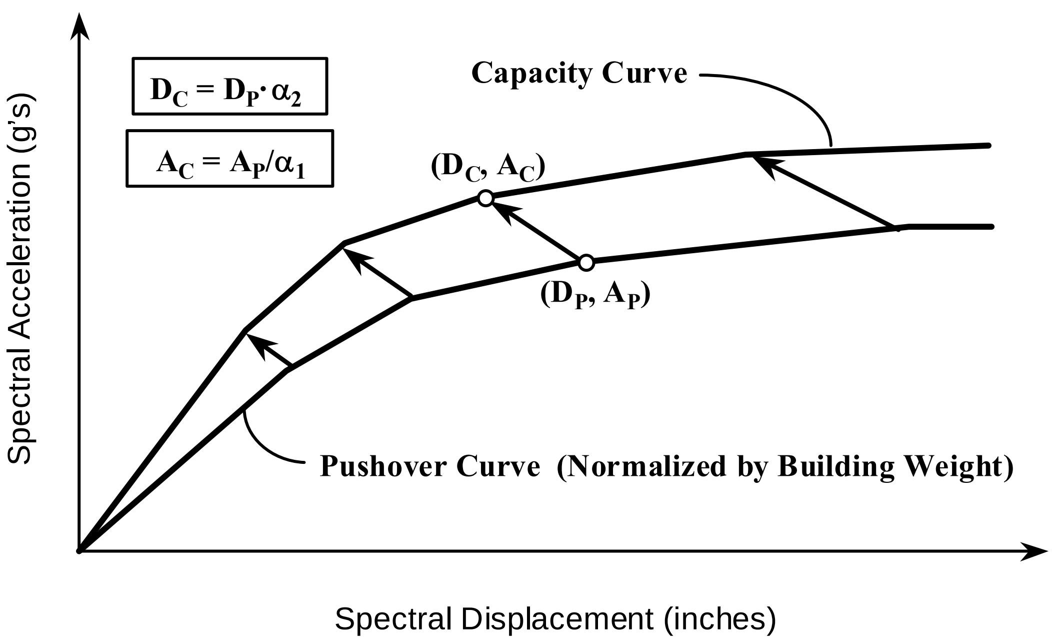


Figure 5.1. Example Conversion of Pushover Curve to Capacity Curve Using Pushover Mode Factors

Hazus defines the two pushover mode factors:

α_1 fraction of building weight effective in pushover mode

α_2 fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement.

Consistent with *ATC-40* methods (and terms), α_1 is defined by the distribution of building mass and pushover mode shape:

$$\alpha_1 = \frac{\left[\sum_{i=1}^{N}(w_i\phi_{ip})/g\right]^2}{\left[\sum_{i=1}^{N}(w_i)/g\right]\left[\sum_{i=1}^{N}(w_i\phi^2_{ip})/g\right]} \tag{5-1}$$

Where: w_i/g = mass assigned to the i[th] degree of freedom

ϕ_{ip} = amplitude of pushover mode at i[th] degree of freedom.

Typically, the shape of the pushover mode is based on the 1[st]-mode of the building in the direction of interest. In general, the pushover mode shape is amplitude dependent, after elements and components begin to yield. While the most appropriate pushover shape would be the amplitude-dependent shape at the amplitude of interest, the pre-yield (1[st]-mode) shape may be used to calculate α_1 without significant loss of accuracy. This statement does not apply to element/component demands that are directly related to the post-yield changes to pushover mode shape. The term "degree of freedom" is used herein, rather than the term "level" of *ATC-40*, to indicate that there may be more than one node (degree of freedom) per floor (e.g., buildings with flexible diaphragms would need several nodes to represent diaphragm response).

Consistent with *ATC-40* (and discussion of the C_0 factor in the commentary of the *NEHRP Guidelines*), the modal factor, α_2, is defined by amplitude of the normalized pushover mode shape at the control point and the pushover mode participation factor:

$$\alpha_2 = \frac{1}{PF_p\varphi_{cp,p}} = \frac{\sum_{i=1}^{N}(w_i\phi^2_{ip})/g}{\left[\sum_{i=1}^{N}(w_i\phi_{ip})/g\right]\varphi_{cp,p}} \tag{5-2}$$

Where: w_i/g = mass assigned to the i[th] degree of freedom

ϕ_{ip} = amplitude of pushover mode at i[th] degree of freedom

$\phi_{cp,p}$ = amplitude of pushover mode at control point.

Typically, the roof is used as the location of the control point. The shape of the pushover mode is typically based on the 1[st]-mode of the building in the direction of interest and is, in general, amplitude dependent after elements and components begin to yield. As for the α_1 term, the most appropriate pushover shape would be the amplitude-dependent shape at the amplitude of interest, but the pre-yield (1[st]-mode) shape may be used to calculate α_2 in most cases without significant loss of accuracy.

The pushover mode factors are used directly to calculate the capacity curve from the pushover curve where each point on the capacity curve is defined by a spectral displacement, SD, and a spectral acceleration, SA:

$$SD = \alpha_2 \Delta_{cp} \tag{5-3}$$

$$SA = \frac{V/\ W}{\alpha_1} \tag{5-4}$$

Where: Δ_{cp} = Pushover control point (e.g., roof) displacement
V = Pushover base shear force (kips)
W = Building weight (kips).

Certain structural analysis software programs (e.g., SAP2000 Nonlinear) automatically convert pushover curves to capacity curves using these formulas.

5.2.2 Yield and Ultimate Capacity Control Points

Capacity curve control points are determined from the capacity curve using both judgment and the following rules:

- Yield capacity control point (**D_y, A_y**) is selected as the point where significant yielding is just beginning to occur (slope of capacity curve is essentially constant up to the yield point).
- The expected period, **T_e**, of the building, at or just below yield, should be the true "elastic" fundamental-mode period of the building:

$$T_e \cong 0.32\sqrt{\frac{D_y}{A_y}} \tag{5-5}$$

- Ultimate capacity control-point acceleration, **A_u**, is selected as the point of maximum spectral acceleration (maximum building strength), not to exceed the value of spectral acceleration at which the structure has just reached its full plastic capacity (i.e., ignore additional straining at the point at which the structure becomes a mechanism).
- Ultimate capacity control-point displacement, **D_u**, is selected as the greater of either the spectral displacement at the point of maximum spectral acceleration or the spectral displacement corresponding to Equation (5-6):

$$D_u = 2 \cdot D_y \frac{A_u}{A_y} \tag{5-6}$$

The *Hazus* definition of the elastic period, **T_e**, is the same as the initial period, T_i, of the *NEHRP Guidelines* and should not be confused with the definition of the effective period, T_e, of the *NEHRP Guidelines*. The effective period, T_e, of the *NEHRP Guidelines* is based on stiffness at 60% of the ultimate strength of the building and should not be used with *Hazus* methods since it could significantly overestimate pre-yield displacement of the building.

Three sets of pushover and capacity curves and the **Control Points** selected for each using the rules described above are shown in Figures 5.2, 5.3 and 5.4, respectively. As shown in these figures, capacity curves typically extend beyond "ultimate" control-point displacement, **D_u**, which defines the displacement at which the system is assumed to be fully plastic, but has not necessarily failed. The median values of fragility curves, described in the next section, define various states of damage along the *Hazus*-compatible capacity curve.

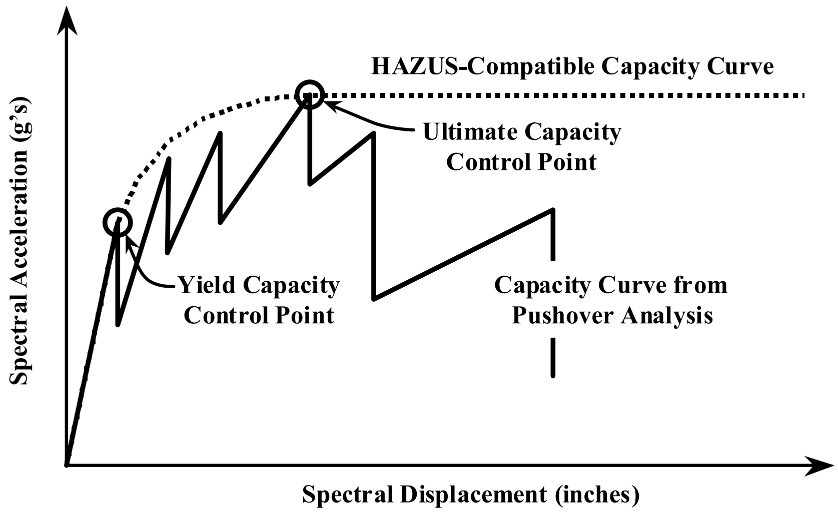


Figure 5.2. Example Development of the Capacity Curve for a Structure with "Saw-Tooth" Force-Deflection Behavior

In Figure 5.2, the first set of curves is for a structure that sustains shear failure and load reduction in a number of components at different levels of spectral displacement. The sequential shear failure of components creates a "saw-tooth" effect that is enveloped by the *Hazus* capacity curve. In Figure 5.3, the second set of curves represents "brittle" force-deflection behavior and catastrophic failure of the structure. The **Ultimate Capacity Control Point** is actually selected to be past the point of failure. This is not inappropriate, since the ultimate point does not define the fragility of the building, only the plateau of the capacity curve.

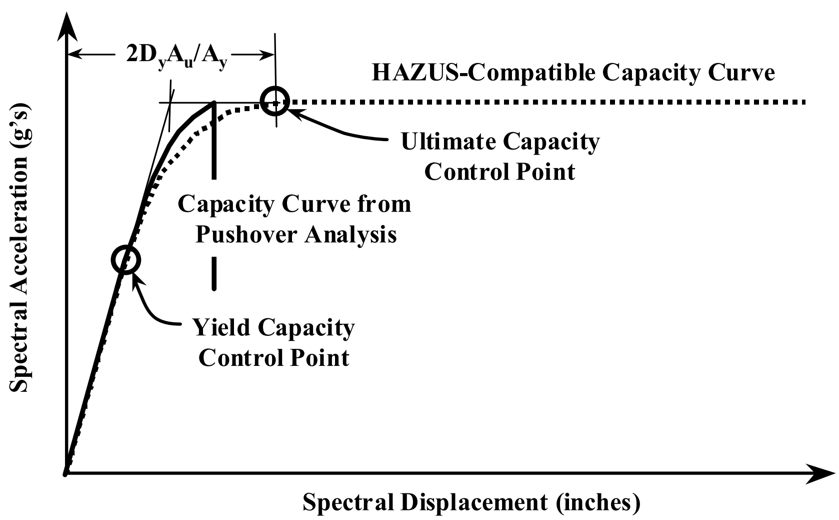


Figure 5.3. Example Development of the Capacity Curve for a Structure with "Brittle" Force-Deflection Behavior

The third set of curves shown in Figure 5.4 illustrate force-deflection behavior of a "ductile" building up to the formation of a complete mechanism (fully plastic state). The pushover curve indicates some additional strength beyond the fully plastic state due to strain hardening assumptions.

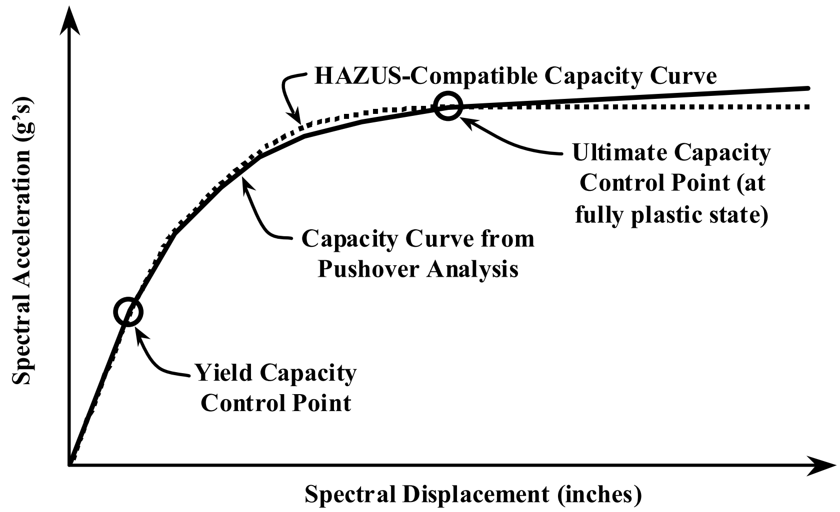


Figure 5.4. Example Development of the Capacity Curve for a Structure with "Ductile" Force-Deflection Behavior

Both the initial stiffness (i.e., elastic period, $\mathbf{T_e}$) and ultimate strength of the capacity curve will, in general, degrade with repeated cycles of post-yield earthquake demand. The effects of degradation of stiffness and strength on capacity and response of the building are accounted for by degradation factors. Development of degradation factors is described in the next subsection.

5.3 Development of Response Parameters

Response parameters include **Elastic Damping** and degradation (**Kappa**) factors that reduce hysteretic damping and affect the intersection capacity and demand, and the fraction of nonstructural components at lower-floors ($\mathbf{F_{NS}}$) which affects the calculation of demand on nonstructural-acceleration sensitive components. Background on the use of the elastic damping and degradation factors in the calculation of response is given in the following subsection.

5.3.1 Response Calculation

Hazus characterizes ground shaking using a standard response spectrum shape, consistent with the format and parameters of the 1997 *NEHRP Provisions* and the *NEHRP Guidelines*. The standard shape consists of two primary parts: (1) a region of constant spectral acceleration at short periods and (2) a region of constant spectral velocity at long periods. Short-period spectral acceleration, S_S, is defined by 5%-damped spectral acceleration at a period of 0.3 seconds. The constant spectral velocity region has spectral acceleration proportional to 1/T and is anchored to the 1-second, 5%-damped spectral acceleration, S_1. A region of constant spectral displacement exists at very long periods, although this region does not usually affect calculation of building damage. Amplification of ground shaking to account for local site conditions is based on the short-period (F_A) and velocity-domain (F_V) soil factors of the 1997 *NEHRP Provisions.*

Hazus modifies elastic system properties to simulate inelastic response by use of "effective" stiffness and damping properties of the building. Effective stiffness properties are based on secant stiffness, and effective damping is based on combined viscous and hysteretic measures of dissipated energy. Effective damping greater than 5% of critical is used to reduce spectral demand in a manner similar to the capacity-spectrum method of *ATC-40*.

Figure 5.4 illustrates the process of developing an inelastic response (demand) spectrum from the 5%-damped elastic response (input) spectrum. The demand spectrum is based on elastic response divided by amplitude-dependent damping reduction factors (i.e., R_A at periods of constant acceleration and R_V at periods of constant velocity). The demand spectrum intersects the building's capacity curve at the point of peak response displacement, D, and acceleration, A. The amount of spectrum reduction typically increases for buildings that have reached yield and dissipate hysteretic energy during cyclic response.

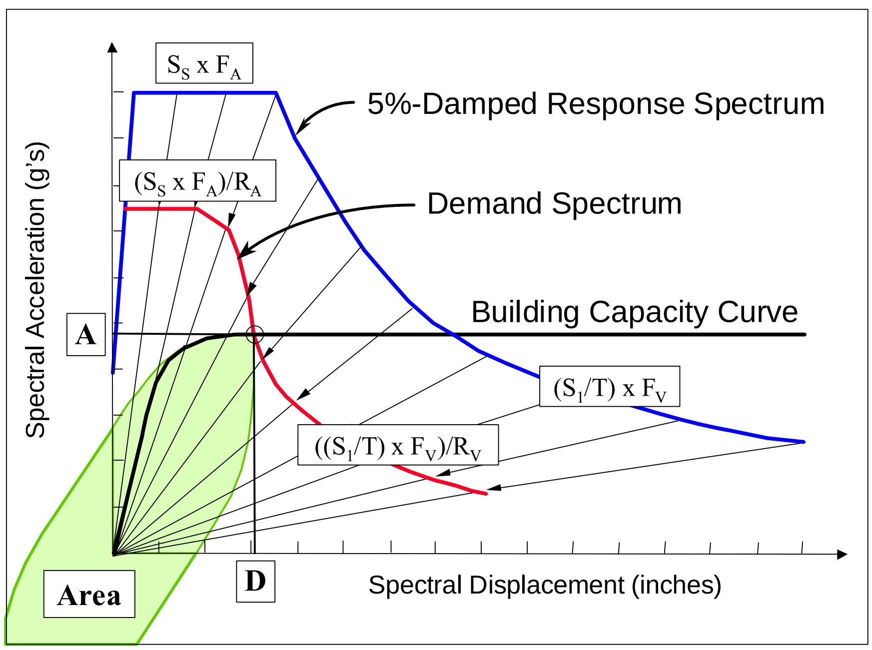


Figure 5.4. Example Demand Spectrum Construction and Calculation of Peak Response Point (D, A)

Spectrum reduction factors are a function of the effective damping of the building, β_{eff}, as defined by Equations (5-8) and (5-9):

$$R_A = 2.12/(3.21 - 0.68\ln(\beta_{eff})) \quad (5\text{-}8)$$

$$R_V = 1.65/(2.31 - 0.41\ln(\beta_{eff})) \quad (5\text{-}9)$$

These equations are based on the formulas given in Table 2 of *Earthquake Spectra and Design* [Newmark and Hall, 1982] for construction of elastic response spectra at different damping levels (expressed as a percentage of critical damping). The factors of Newmark and Hall represent all site classes (soil profile types), but distinguish between domains of constant acceleration and constant velocity. For either domain, the reduction factor is the ratio of 5%-damped response to response of the system with β_{eff} damping. Equations (5-8) and (5-9) yield reduction values of $R_A = 1.0$ and $R_V = 1.0$, respectively, for a value of $\beta_{eff} = 5\%$ of critical.

Effective damping, β_{eff}, is defined as the total energy dissipated by the building during peak earthquake response and is the sum of an elastic damping term, β_E, and a hysteretic damping term, β_H, associated with post-yield, inelastic response:

$$\beta_{eff} = \beta_E + \beta_H \tag{5-10}$$

The elastic damping term, β_E, is assumed to be a constant (i.e., amplitude independent) and follows the recommendations of Table 3 of *Earthquake Spectra and Design* for materials at or just below their yield points. The hysteretic damping term, β_H, is dependent on the amplitude of post-yield response and is based on the area enclosed by the hysteresis loop at peak response displacement, D, and acceleration, A, as shown in Figure 5.5. Hysteretic damping, β_H, is defined in Equation (5-11):

$$\beta_H = \kappa \left(\frac{\text{Area}}{2\pi \, D \, A} \right) \tag{5-11}$$

Where:

- Area — is the area enclosed by the hysteresis loop, as defined by a symmetrical push-pull of the building capacity curve up to peak positive and negative displacements, ± D, assuming no degradation of components,
- D — is the peak displacement response of the capacity curve,
- A — is the peak acceleration response at peak displacement, D
- κ — is a degradation factor that defines the fraction of the Area used to determine hysteretic damping.

For a value of $\kappa = 1.0$, Equation (5-11) may be recognized as the definition of equivalent viscous damping, found in modern vibration textbooks [e.g., Chopra, 1995] and traceable to the early work of Jacobsen [1930] and others. The κ (Kappa) factor in Equation (5-11) reduces the amount of hysteretic damping as a function of model building type, seismic design level and shaking duration to simulate degradation (e.g., pinching) of the hysteresis loop during cyclic response. Shaking duration is described qualitatively as either short, moderate or long, and is assumed to be primarily a function of earthquake magnitude, although proximity to fault rupture can also influence the duration of the level of shaking that is most crucial to building damage.

Figure 5.6 shows a typical capacity curve and three example demand spectra for damping levels corresponding to short ($\kappa_S = 0.8$), moderate ($\kappa_M = 0.5$) and long ($\kappa_L = 0.3$) duration ground shaking, respectively. In this example, building displacement due to long-duration ground shaking is more than twice that due to short-duration ground shaking (although building acceleration does not increase). Damage to the structural system and nonstructural, drift-sensitive components and related losses increase significantly with increase in the duration of ground shaking for buildings that have reached yield.

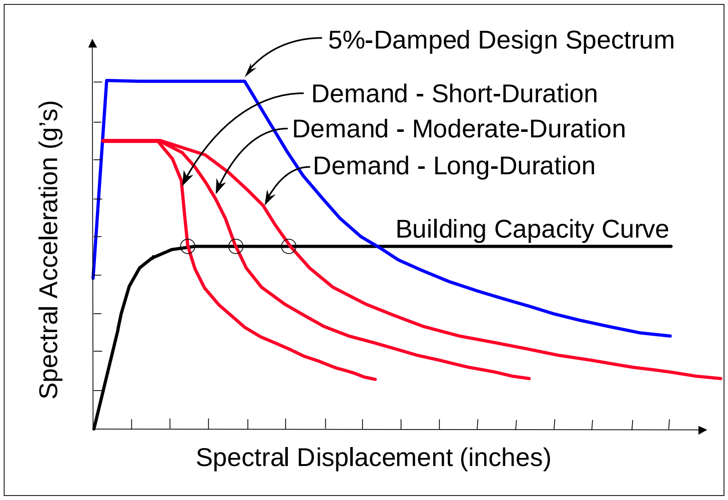


Figure 5.6. Example Demand Spectra – Post-Yield Response due to Strong Ground Shaking of Either Short, Moderate or Long-Duration

5.3.2 Elastic Damping Factors

As described in the preceding subsection, **Elastic Damping** factors estimate the damping of the building at or just below yield of the structural system. These values should be selected on the basis of the building type, reflecting the inherent differences in the damping behavior of different materials. In general, the **Elastic Damping** factors included in *Hazus* for general building stock should be used without modification for building-specific applications. Table 5.1 summarizes the **Elastic Damping** values of *Hazus* for different building types.

Table 5.1 Suggested Elastic Damping Values

Building Type by Material	Damping (% of Critical)
Mobile Home	5%
Steel Buildings	5% - 7%
Reinforced-Concrete and Pre-cast Concrete Buildings	7%
Reinforced-Masonry Buildings	7% - 10%
Unreinforced-Masonry Bearing-Wall and In-Fill Buildings	10%
Wood Buildings	10% - 15%

5.3.3 Degradation Factors

Degradation (**Kappa**) factors are a function of the expected amplitude and duration (number of cycles) of post-yield building response. These parameters depend on the level of ground shaking, which is different for each building site and scenario earthquake. The default values of the **Kappa** factor developed for generic-building analysis assume that the building would have ground shaking strong enough to effect significant post-yield response of the structure, and degradation is based on the magnitude of the scenario event. The larger the magnitude of the event, the longer the assumed duration of ground shaking. In this sense, earthquake magnitude became a surrogate indicator of the duration of post-yield response, assuming shaking was strong enough to push the structure beyond the yield point. It should be recognized that if the ground shaking were not strong enough to yield the building, there would be little or no degradation, regardless of the magnitude of the scenario earthquake (or the type of structural system).

Kappa factors should be selected considering the extent to which brittle failure of the elements and components reduces the strength of the structural system. The capacity curve developed by pushover analysis provides some guidance on the selection of appropriate **Kappa** factors. If the capacity curve indicates a loss of strength at the ultimate capacity control point, then the **Kappa** factor should indicate a somewhat proportional reduction in hysteretic loop area. For example, in Figure 5.1 the capacity curve indicates about a 50% reduction in full strength, and a commensurate amount of degradation would be appropriate (e.g., $\kappa_M = 0.50$ for a moderate duration of post-yield response). In Figure 5.2, the capacity curve indicates nearly complete (brittle) failure (at the ultimate capacity control point) and a very low value of the degradation factor would be appropriate (e.g., $\kappa_M = 0.10$ for a moderate duration of post-yield response). In Figure 5.3, the capacity curve indicates nearly fully ductile behavior, and a relatively high value of the degradation factor would be appropriate (e.g., $\kappa_M = 0.90$ for a moderate duration of ground shaking).

Table 5.2 provides some general guidance on the selection of the degradation (**Kappa**) factor. The Kappa factors are shown as a function of the level of response (i.e., one-half yield, yield and post-yield levels of peak response) and for post-yield response as a function of post-yield shaking duration (i.e., short, moderate and long). The table also relates suggested values of Kappa factors to the seismic design level and quality of construction used to characterize generic building types of *Hazus*.

Table 5.2 Suggested Values of the Degradation (Kappa) Factor

Design Level and Construction Quality						Degradation (Kappa) Factor				
	Seismic Design Level[1]					At ½ Yield	At Yield	Post-Yield Shaking Duration		
	SHC	HC	MC	LC	PC			Short	Moderate	Long
QC[2]	S	S				1.0	1.0	1.0	0.9	0.7
		O	S			1.0	1.0	0.9	0.7	0.5
		I	O	S		1.0	0.9	0.7	0.5	0.3
			I	O	S	1.0	0.7	0.5	0.3	0.1
				I	O	1.0	0.5	0.3	0.1	0.0

1. Seismic Design Level Designation – Special High-Code (SHC), High-Code (HC), Moderate-Code (MC), Low-Code (LC) and Pre-Code (PC)
2. Construction Quality (QC) Designation – Superior (S), Ordinary (O) and Inferior (I)

The suggested values of the Kappa factor given in Table 5-2 do not apply to seismically rehabilitated buildings. If the user is developing damage functions for a building that been strengthened, or otherwise seismically improved, then the selection of Kappa's should be based on a seismic design level and quality of construction that reflects these improvements. For example, substantial seismic rehabilitation of a Pre-Code building of Ordinary construction (i.e., older building constructed before seismic codes were adopted) might now be considered to be equivalent to a building of Moderate Code seismic design level of Superior construction quality. Of course, the amount by which the seismic design level and/or construction quality should be increased depends on the type and extent of the seismic improvements made to the structural system.

5.3.4 Fraction of Nonstructural Components at Ground Level

The fraction of nonstructural components at the ground level ($\mathbf{F_{NS}}$) is used in the methodology to determine the portion of nonstructural acceleration-sensitive components (and contents) at lower floors. At this level, peak ground acceleration, rather than spectral acceleration is used for evaluation of nonstructural components (and contents). In determining the nonstructural fraction, the user should base the fraction on the value of nonstructural acceleration-sensitive components and contents. If most of the value of such components happens to be at lower floors (e.g., very expensive equipment is located in the basement), then direct economic losses should be based on ground shaking defined by peak ground acceleration. In contrast, if all of the valuable mechanical equipment is located in a roof penthouse, then peak floor acceleration (based on spectral acceleration) should be used to estimate direct economic loss.

SECTION 6

DEVELOPMENT OF FRAGILITY CURVES

6.1 Building Response and Performance Criteria

This section guides users in the development of fragility curves parameters that are used by Advanced Engineering Building Module (AEBM) to calculate damage as a function of building response. It is assumed (and essential) that the user has already performed a detailed nonlinear static (pushover) analysis of the building that conforms essentially to the methods of the *NEHRP Guidelines* (or *ATC-40*) and to certain other criteria as set forth in this section (and Section 5).

The pushover analysis must appropriately capture the damage patterns of elements and components of the building and evaluate modes of building failure (i.e., partial or full collapse of the structure). As previously discussed in Section 5.1, users must carefully consider modes of building failure and develop appropriate and representative models of structural response and element/component behavior. More than one pushover model could be used to evaluate different modes of response and failure (e.g., of different building segments). Section 6.2 and 6.3 assume that the user has resolved building complexity and describe methods for developing fragility parameters from a single pushover analysis.

There are certain key aspects to the damage functions of which users must be aware when developing fragility parameters. First, the damage functions should predict damage without bias such as that inherent to the conservatism of seismic design codes and guidelines. In general, limit states of the *NEHRP Guidelines* (or *ATC-40*) will under-predict the capability of the structure, particularly for the more critical performance objectives, such as Collapse Prevention (CP). The *NEHRP Guidelines'* criteria for judging CP certainly do not intend that 50 out of 100 buildings that just meet CP limits would collapse. Most engineers would likely consider an acceptable fraction of CP failures (given that buildings just meet CP criteria) to be between 1 and 10 in every 100 buildings. In contrast, the median drift value of the Complete structural damage state of *Hazus* is the amount of building displacement that would cause, on the average, 50 out of 100 buildings of the building type of interest to have Complete damage (e.g., full financial loss). In general, users should not derive median values of *Hazus* damage states directly from the performance limits of the *NEHRP Guidelines* (and *ATC-40*).

Fragility parameters of the more extreme damage states are particularly difficult to estimate since these levels of damage are rarely observed even in the strongest ground shaking. In the 1995 Kobe earthquake, the worst earthquake disaster to occur in a modern urban region, only about 10 in every 100 mid-rise commercial buildings located close to fault rupture had severe damage or collapse. Typically, the fraction of modern buildings with such damage (e.g., Complete structural damage) is much less than 10 in 100. In selecting median values of damage states, users should be mindful that median values represent the 50 percentile (e.g., 50 in every 100 buildings have reached the state of damage of interest). Median values of spectral displacement (or spectral acceleration) for the more extensive states of damage may appear large relative to seismic code or guideline design criteria.

Calculation of damage-state probability is a step in the sequential process of estimating earthquake losses. Some leeway is available to users in determining building-specific fragility curves, since the building-specific loss functions will also be developed based on the fragility assumptions. What is essential is that the amount and type of damage associated with each damage state be consistent with the amount and type of damage assumed in the development of loss functions. For example, the user may have a choice of 4 inches, 5 inches or 6 inches of spectral displacement to represent Moderate structural damage to the building. In this example, these spectral displacements represent a range of plausible estimates resulting in "moderate" damage to elements and components, but with distinct differences in the cost of repair. That is, 6 inches of spectral displacement would cause more damage and cost more to repair than 4 inches of spectral displacement. The user may choose either 4 inches, 5 inches or 6 inches of spectral displacement to represent Moderate structural damage, provided the loss functions for Moderate damage are developed for the same amount of spectral displacement.

Fragility curves define boundaries between damage states. That is, the median value of the Damage State of interest defines the threshold of damage, and this state of damage is assumed to exist up to next state of damage. This description is illustrated in Figures 6.1, which includes example fragility curves for Slight, Moderate, Extensive and Complete structural damage. In this illustration, a shaded region illustrates the probability-response space associated with Moderate damage. The boundary on the left of the shaded region is defined by the fragility curve for Moderate (or greater) structural damage, and the boundary on the right of the shaded region is defined by the fragility curve for Extensive (or greater) damage. The probability of Moderate damage at a given level of spectral demand is calculated as the difference of the probability of Moderate (or greater) damage less the probability of Extensive (or greater) damage – a probability of 0.40 at 6 inches of spectral displacement in the example shown in Figure 6.1.

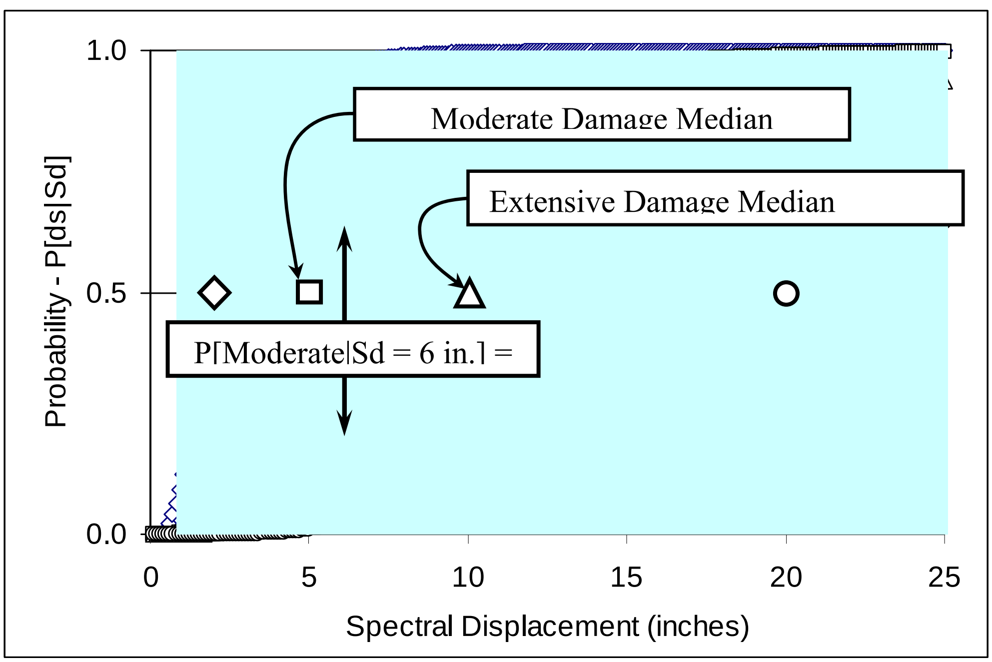


Figure 6.1. Example Fragility Curves - Calculation of Damage-State Probability

The slope of the fragility curve is controlled by the lognormal standard deviation value (Beta). The smaller the value of Beta, the less variable the damage state, and the steeper the fragility curve. The larger the value of Beta, the more variable the damage state, and the flatter the fragility curve. Figure 6.2 illustrates this trend for fragility curves that share a common median (i.e., spectral displacement of 5 inches), but have Beta values ranging from 0.4 to 1.2. This range of Beta values approximately covers the range of Beta values that could be used for building-specific fragility curves.

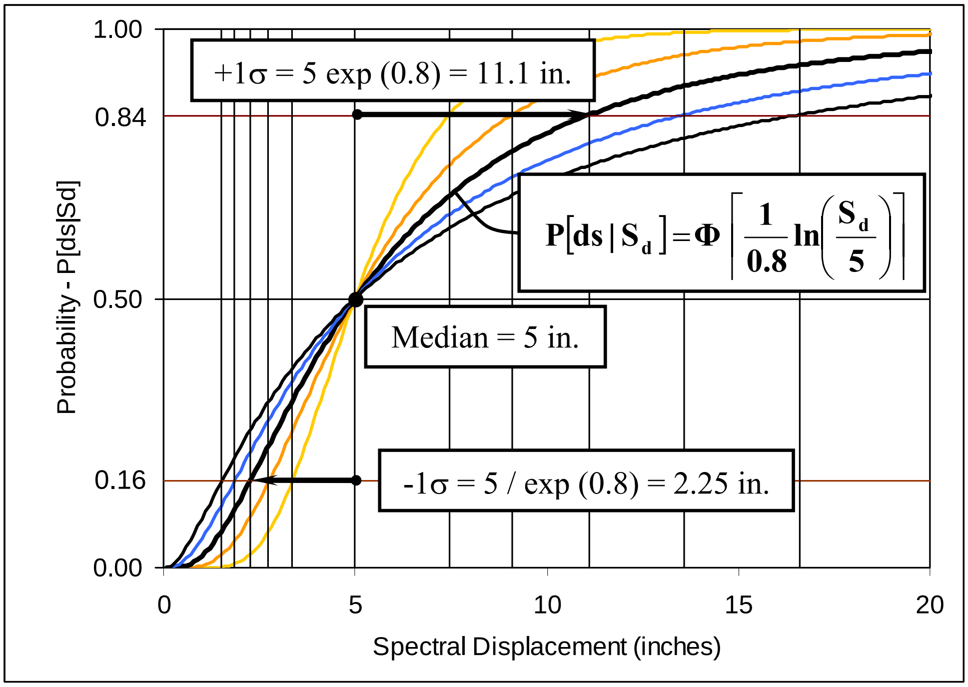


Figure 6.2. Example Lognormal Fragility Curves (Beta = 0.4, 0.6, 0.8, 1.0 and 1.2) and Calculation of ± 1σ Spectral Displacement

Figure 6.2 illustrates the calculation of spectral displacement at ± 1 standard deviation (± 1σ) probability levels for a typical Beta value of 0.8. In this example, the +1σ level of spectral displacement is more than twice the median value (and the -1σ level of spectral displacement is less than one-half the median value) for a Beta value of 0.8 which illustrates the large amount of variability typical of *Hazus* fragility curves.

6.2 Development of Damage-State Medians

Development of **Damage-State Medians** involves three basic steps:

- Develop a detailed understanding of damage to elements and components as a continuous function of building response (e.g., average inter-story drift or floor acceleration)
- Select specific values of building response that best represent the threshold of each discrete damage state
- Convert damage-state threshold values (e.g., average inter-story drift) to spectral response coordinates (i.e., same coordinates as those of the capacity curve).

In general, the implementation of the three steps will be significantly different for structural and nonstructural systems. It is expected that detailed pushover analysis of the building will be the primary source of information regarding structural damage and selection of appropriate damage-state threshold values. In most cases, generic-building fragility values of *Hazus* would not be used for the structural system (but could provide a "sanity check" of building-specific results). In contrast, pushover analysis typically provides only minimal information of nonstructural system performance, and users will rely primarily on the generic-building fragility values of *Hazus* to determine threshold values of nonstructural damage states.

6.2.1 Structural System

Selection of **Damage-State Medians** should be consistent with the broad descriptions of structural damage given in Section 5.3.1 of the *Hazus-MH 2.1 Technical Manual* for different model building types. Descriptions of damage in *Hazus* are sufficiently vague to permit user selection of values that best fit the damage patterns of dominant elements and components of the structural system. In addition, general guidance is provided below in Table 6.1 regarding the selection of appropriate **Damage-State Medians** for the structural system.

Table 6.1. General Guidance for Selection of Structural Damage-State Medians

Damage State	Likely Amount of Damage, Direct Economic Loss, or Building Condition			
	Range of Possible Loss Ratios	Probability of Long-Term Building Closure	Probability of Partial or Full Collapse	Immediate Post-Earthquake Inspection
Slight	0% - 5%	P = 0	P = 0	Green Tag
Moderate	5% - 25%	P = 0	P = 0	Green Tag
Extensive	25% - 100%	P ≅ 0.5	P ≅ 0[1]	Yellow Tag
Complete	100%	P ≅ 1.0	P > 0	Red Tag

1. Extensive damage may include local collapse (e.g., out-of-plane failure of URM infill walls).

Pushover analysis results typically express performance in terms of component ductility demand, rather than in terms of physical damage. The structural criteria of Table 2-4 (Vertical Elements) and Table 2-5 (Horizontal Elements) of the *NEHRP Guidelines* provide some description of damage expected at various performance levels (e.g., component ductility) and may be used to relate element and component performance to physical description of damage. It is expected that the results of the pushover analysis, whether expressed in terms of physical damage (e.g., crack size) or in terms of component ductility demand, will be sufficient for users to tabulate the type and sequence of damage (and failure) of elements and components.

Damage to elements and components of the structural system should be tabulated as a function of the lateral displacement of the building, quantified by the average inter-story drift ratio (i.e., roof displacement divided by building height). Of course, individual stories of multi-story building would not all be expected to have the same drift, nor would inter-story drift be the same at all locations on a given floor if there was diaphragm flexibility or a rotational component to the pushover mode shape. However, average inter-story drift provides a convenient measure of building response that may be compared against default values of average inter-story drift that define damage states for generic building types of *Hazus*.

The *NEHRP Guidelines* provide acceptance criteria that define deformation limits for large number of structural components and elements of different material types. These acceptance criteria imply various degrees of component or element damage and thus may be used to determine appropriate values of the average inter-story drift ration for each damage state of the structural system. However, in using the acceptance criteria of the *NEHRP Guidelines* users must be aware and account for each of the following four issues:

- Conservative Deformation Limits – The deformation limits of the *NEHRP Guidelines* are, in general, conservative estimates of true component or element capacity. In concept, the deformation limits are based on "backbone" curves that represent average multi-linear behavior of the subassembly of interest (e.g., as determined by cyclic-load testing). However, control points of idealized backbone curves necessarily incorporate some conservatism (that could be removed if the component or element were tested). Further, the Collapse Prevention deformation limits of primary components or elements are defined as 75% of that permitted for secondary elements, reflecting added conservatism for design of primary components or elements. The *NEHRP Guidelines* (like other seismic "codes") include inherent conservatism in limit states. While appropriate for design, conservatism should be removed from deformation limits used to estimate actual damage and loss.

- Deformation Limits vs. Damage States – The *NEHRP Guidelines* provide limits on component or element deformation rather than explicitly defining damage in terms of degree of concrete cracking, nail pull-out, etc., or whether component of element damage is likely to repairable (or not). For estimating direct economic loss it is important to understand the type of damage, not just the degree of yielding, to establish if repair would be required and what the nature (and cost) of such repairs would be.

- Global vs. Local Damage – Local damage (as inferred from the deformation limits of the *NEHRP Guidelines*) of individual components and elements must be accumulated over the entire structure to represent a global damage state. In general, any number of different combinations of local damage to components and elements could result in the same amount of global damage. Moderate damage could result due to a modest amount of damage to many components of elements, but would most likely be caused by significant damage to a limited number of components or elements that would cost 5% to 25% of the value of the structural system to repair (or replace).

- Collapse Failure – In general, collapse failures of the structural system require consideration of the interaction of components and elements and evaluation of possible global instability. The *NEHRP Guidelines* define "Collapse Prevention" deformation limits for components that are intended (with some degree of conservatism) to avoid local structural failure of components and elements. Reaching the "Collapse Prevention" deformation limit of components or elements does not necessarily imply structural collapse. Typically, structural systems can deform significantly beyond "Collapse Prevention" deformation limits before actually sustaining a local or global instability. It should be noted that while only a few buildings have actually collapsed during a major earthquake, case studies of the *NEHRP Guidelines* found that "Collapse Prevention" deformation limits were typically exceeded for strong ground shaking [FEMA, 1999].

Table 6.2 provides general guidance to users wishing to relate deformation (or deformation ratio) limits of the *NEHRP Guidelines* to average inter-story drift ratios of structural damage states. Table 6.2 provides two sets of criteria for each structural damage state. The first set of criteria establish damage states in terms of the fraction (by replacement value) of structural components reaching the control point "C" (or control point "E") on the idealized load versus deformation (backbone) curve. The second set of criteria establish an upper-bound on the average inter-story drift ratio of damage states by factors applied to the displacement at which 50% of structural components have reached their individual yield points (i.e., control point "B"). Figure 6.3 (taken from Figure 2-5 of the *NEHRP Guidelines*, illustrates points B, C and E on the idealized load versus deformation (backbone) curve.

Table 6.2. General Guidance for Relating Component (or Element) Deformation to the Average Inter-Story Drift Ratios of Structural Damage-State Medians

Damage State	Component (Criteria Set No. 1)[1]			Component (Criteria Set No. 2)[1]		
	Fraction[2]	Limit[3]	Factor[4]	Fraction[2]	Limit[3]	Factor[4]
Slight	> 0%	C	1.0	50%	B	1.0
Moderate	≥ 5%	C	1.0	50%	B	1.5
Extensive	≥ 25%	C	1.0	50%	B	4.5
Complete	≥ 50%	E	1.0 - 1.5[5]	50%	B	12

1. The average inter-story drift ratio of structural damage state is lessor of the two drift ratios defined by Criteria Sets No. 1 and No.2, respectively.
2. Fraction defined as the repair or replacement cost of components at limit divided by the total replacement value of the structural system.
3. Limit defined by the control points of Figure 6-2 and the acceptance criteria of *NEHRP Guidelines*.
4. Factor applied to average inter-story drift of structure at deformation (or deformation ratio) limit to calculate average inter-story drift ratio of structural damage-state median.
5. Complete factor is largest value in range for which the structural system is stable.

As an example of the use of the 1st set of criteria of Table 6-2 (i.e., limits of 2nd criteria set are assumed not to govern), consider the development of damage-state medians for the "pushover" curve shown in Figure 6-4. This pushover curve corresponds to the "saw-tooth" capacity curve shown previously in Section 5, except that curve is now shown in terms of base shear versus average inter-story drift ratio (i.e., roof displacement normalized by building height. This pushover curve is assumed to have been developed by nonlinear static analysis of the structure using the modeling and acceptance theory of the *NEHRP Guidelines*.

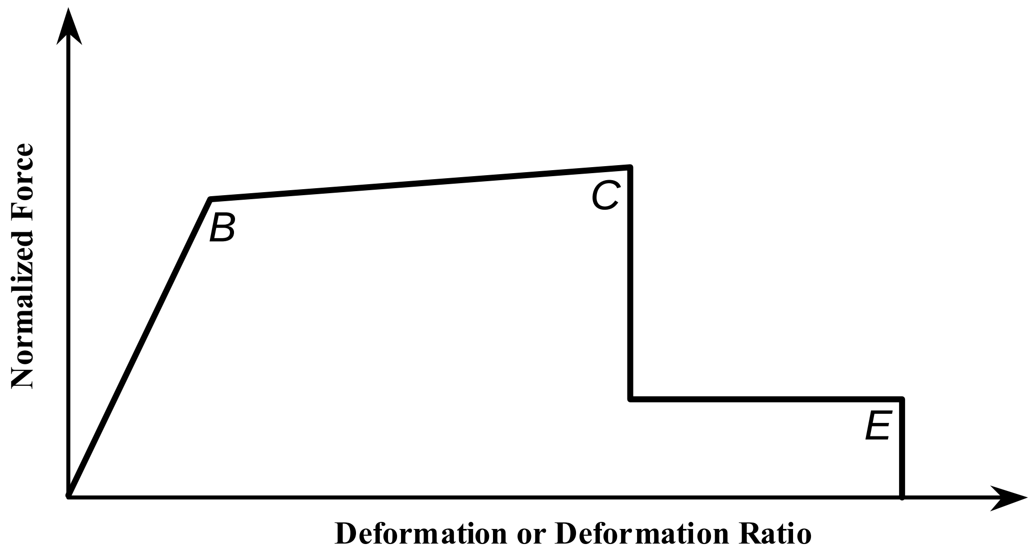


Figure 6.3. Idealized Component Load versus Deformation Curve (from Figure 2-5 of the NEHRP Guidelines)

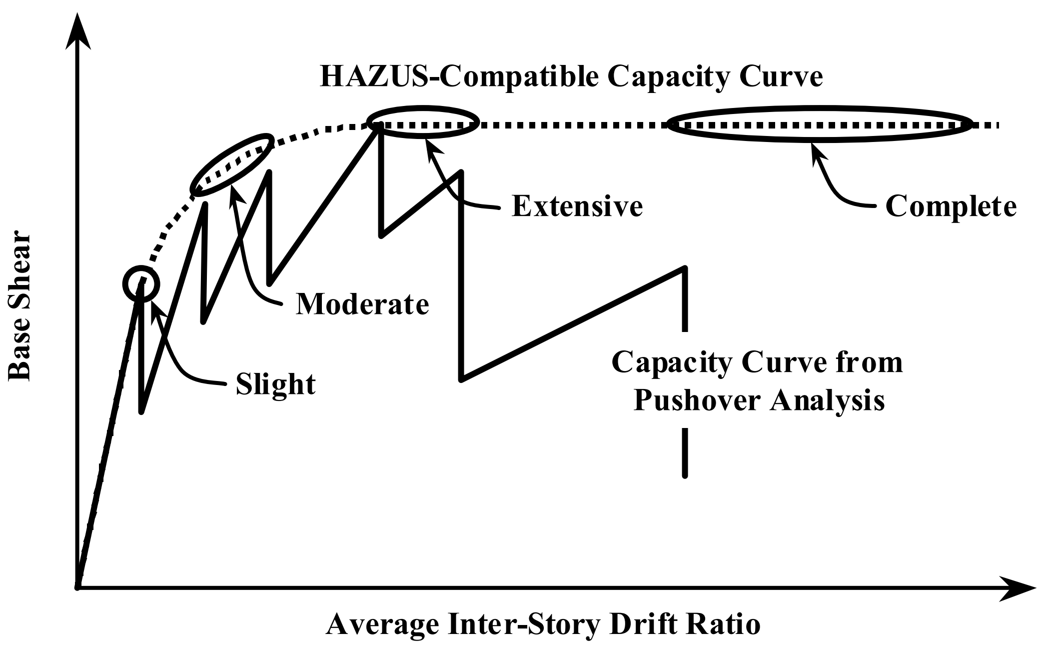


Figure 6.4. Example Damage-State Medians of "Saw-Tooth" Pushover Curve

Following the guidance of Table 6-2, the median of Slight damage is defined by the first structural component to reach control point C on its load deformation curve (i.e., point where component capacity of component drops, as illustrated in Figure 6.3). On a global basis, this point may be recognized as the first "tooth" of the capacity curve (i.e., point where structure capacity drops abruptly, as illustrated in Figure 6.4).

Moderate damage is defined by a median value for which a sufficient number of components have each reached control point C (on their respective load deformation curves) such that it will cost at least 5% of the replacement value of the structural system to repair (or replace) these components. Moderate damage is likely to be localized, since only a limited number of components can be repaired (or replaced) for 5% of the replacement value of the structural system. In Figure 6.4, an oval indicates that this extent damage might occur at the second or third "tooth" of the capacity curve, depending on type of repair, accessibility of damaged components and other factors that influence repair cost.

Extensive damage is defined by a median value similar to Moderate damage, except that damage repair now costs at least 25% of the value of the structural system. Extensive damage is likely to affect a number of components distributed throughout the building or affect all components at the most vulnerable story. Again, an oval indicates the sensitivity of the median to repair cost factors. The Extensive damage oval extends up to the point on the pushover curve for which there is a large drop in load capacity without significant recovery indicating (in this example) that a large number of elements would require repair or replacement at this level of response.

Complete damage is defined by a median value for which at least 50% (in terms of repair/replacement cost) of structural components have each lost full lateral capacity, as defined by control point E on their respective load deformation curves. Table 6.2 acknowledges the inherent conservatism in the values of control point E (as defined by the *NEHRP Guidelines*) and suggests that the median of the Complete damage state should be as much as 1.5 times greater than control point E, provided that the structure is not likely to collapse.

In Figure 6.4, a large oval indicates the range of possible median values for the Complete damage state. This range extends from 1.0 to 1.5 times the point of the last large drop in the load-carrying capacity of the pushover curve, indicating that most elements have reached their limit. The Complete damage state and related collapse failure modes are the most difficult to rationalize using engineering methods, even when evaluated using the sophisticated nonlinear methods of the *NEHRP Guidelines*. Correlation of predicted and observed damage and losses indicate that very liberal interpretations of engineering acceptance criteria are required to accurately predict Complete damage and the number of collapses that have actually occurred.

The average inter-story drift ratios of structural damage states of generic building types may be found in Table 6.4a and Tables 5.9a through 5.9d of the *Hazus-MH 2.1 Technical Manual*. These tables provide drift ratios of each model building type for Special High-Code, High-Code, Moderate-Code, Low-Code and Pre-Code seismic design levels, respectively. These drift ratios are also summarized below in Table 6.3. The *Hazus* drift ratios for generic buildings may be used as a "sanity check" of building-specific values, recognizing that generic-building damage-state median values represent a typical building of the group and could be a factor of 2 or more greater (or less than) the medians of a specific building.

It should also be noted that Table 6.3 incorporates the effects of diaphragm flexibility (and other contributors to the overall flexibility of the structural system) in the values of average inter-story drift ratio that define the damage-state medians of generic buildings. In contrast, the control points and acceptance criteria of the *NEHRP Provisions* apply strictly to the component of interest. For structural systems with very stiff components (e.g., URM buildings), average inter-story drift ratios developed from pushover analysis using the modeling and acceptance criteria of the *NEHRP Guidelines* should also incorporate diaphragm (and other sources of) flexibility before comparison with the default values summarized in Table 6.3 for generic building types.

Table 6.3. *Hazus* Average Inter-Story Drift Ratio (Δ_{ds}) of Structural Damage States

Model Building Type		Structural Damage States			
		Slight	Moderate	Extensive	Complete
Low-Rise Buildings – High-Code Design Level					
W1, W2		0.004	0.012	0.040	0.100
S1		0.006	0.012	0.030	0.080
C1, S2		0.005	0.010	0.030	0.080
C2		0.004	0.010	0.030	0.080
S3, S4, PC1, PC2, RM1, RM2		0.004	0.008	0.024	0.070
Low-Rise Buildings – Moderate-Code Design Level					
W1, W2		0.004	0.010	0.031	0.075
S1		0.006	0.010	0.024	0.060
C1, S2		0.005	0.009	0.023	0.060
C2		0.004	0.008	0.023	0.060
S3, S4, PC1, PC2, RM1, RM2		0.004	0.007	0.019	0.053
Low-Rise (LR) Buildings – Low-Code Design Level					
W1, W2		0.004	0.010	0.031	0.075
S1		0.006	0.010	0.020	0.050
C1, S2		0.005	0.008	0.020	0.050
C2		0.004	0.008	0.020	0.050
S3, S4, PC1, PC2, RM1, RM2		0.004	0.006	0.016	0.044
S5, C3, URM		0.003	0.006	0.015	0.035
Low-Rise (LR) Buildings – Pre-Code Design Level					
W1, W2		0.003	0.008	0.025	0.060
S1		0.005	0.008	0.016	0.040
C1, S2		0.004	0.006	0.016	0.040
C2		0.003	0.006	0.016	0.040
S3, S4, PC1, PC2, RM1, RM2		0.003	0.005	0.013	0.035
S5, C3, URM		0.002	0.005	0.012	0.028
Mid-Rise Buildings[1]					
All	Mid-Rise Building Types	2/3 * LR	2/3 * LR	2/3 * LR	2/3 * LR
High-Rise Buildings[1]					
All	High-Rise Building Types	1/2 * LR	1/2 * LR	1/2 * LR	1/2 * LR

1. Mid-rise and high-rise buildings have damage-state drift values based on low-rise (LR) drift criteria reduced by factors of 2/3 and 1/2, respectively, to account for higher-mode effects and differences between average inter-story drift and individual inter-story drift.

As the final step in the development of **Damage-State Medians** for the structural system, average inter-story drift values for each damage state are converted to the corresponding amount of spectral displacement using the modal factor, α_2, and other terms:

$$\mathbf{S}_{\mathbf{d,ds}} = \Delta_{ds} \cdot H_R \cdot \alpha_2 \qquad (6\text{-}1)$$

Where:

$\mathbf{S}_{\mathbf{d,ds}}$	=	Median spectral displacement value of damage state, ds (inches)
Δ_{ds}	=	Average inter-story drift ratio at the threshold of damage state, ds, determined by user (consistent with generic values of Table 6.2)
H_R	=	Height of building at the roof level (inches)
α_2	=	Pushover modal factor from Equation (5-2).

6.2.2 Nonstructural Components

In most applications, **Damage-State Medians** for nonstructural components may be based directly on the default values of *Hazus*. Exceptions include buildings with nonstructural components or contents that are either significantly more rugged or significantly more vulnerable than the normal make-up of components of nonstructural systems in a typical commercial building. Examples of buildings with particularly vulnerable systems include certain manufacturing facilities (e.g., buildings with clean rooms), laboratories, computer facilities, historical buildings (architectural components), art museums and other buildings with special contents. Examples of buildings with particularly rugged systems include certain military, industrial or emergency facilities whose nonstructural systems and contents have been specially anchored or braced to resist earthquake shaking.

Hazus default values for the drift ratio of the threshold of each damage state are summarized in Table 6.3 for drift-sensitive nonstructural components. These damage-state drift ratios are assumed to be the same for all building types and seismic design levels. The same values of drift ratio are also assumed to be appropriate for special buildings, such as emergency facilities, since drift-sensitive components (partitions) typically do not receive special design or detailing to accommodate building displacement.

Table 6.4. *Hazus* Damage-State Criteria for Nonstructural Systems and Contents

Design Level	Nonstructural Damage States – All Building Types			
	Slight	Moderate	Extensive	Complete
Inter-Story Drift Ratio (Δ_{ds}) - Drift-Sensitive Components				
All	0.004	0.008	0.025	0.050
Peak Floor Acceleration ($A_{max,ds}$) - Acceleration-Sensitive Components/Contents (g's)				
Special High-Code	0.45	0.9	1.8	3.6
High-Code	0.30	0.6	1.2	2.4
Moderate-Code	0.25	0.5	1.0	2.0
Low-Code	0.20	0.4	0.8	1.6
Pre-Code	0.20	0.4	0.8	1.6

Hazus default values of peak floor acceleration defining the threshold of each damage state are summarized in Table 6.3 for acceleration-sensitive nonstructural components (and contents). These damage-state accelerations are assumed to be the same for all building types, but to vary by seismic design level. Similarly, emergency or other facilities that have special anchorage and bracing requirements for nonstructural components and equipment (Special High-Code design level) have damage-state accelerations increased by a factor of 1.5.

Considering the importance to the estimates of certain types of loss, in particular estimates of direct economic loss, it would seem desirable to develop building-specific damage-state parameters for nonstructural components and contents, rather than rely on generic building data. However, rigorous development of nonstructural parameters would require detailed evaluation of component capacity, similar to that used to evaluate the structural system, only much more difficult to perform due to the complexity and variety of different nonstructural systems and components. Nonstructural systems and contents would need to be thoroughly inspected (detailed field survey). Capacity of anchorage and bracing would need to be evaluated (possibly requiring dynamic analysis of complex systems such as piping runs). Fragility values would then need to be developed based on the results of the analysis, available test data (e.g., of similar equipment), and/or experience data. This process is not practical for most applications and would likely be limited to a "walk-down" of nonstructural systems and building contents.

If the user has access to the building and is concerned that nonstructural components and/or contents are not "typical," then it is recommended that a building "walk-down" be performed using checklists and other guidance provided by *FEMA 74* [FEMA, 1994] or *FEMA 310* [FEMA, 1998]. These documents do not estimate damage or loss but are useful in spotting potential deficiencies in typical nonstructural systems. The user need not perform calculations, but may rely on judgement to estimate the approximate drift ratio (for drift-sensitive components) or peak floor acceleration (for acceleration-sensitive components) at which different nonstructural components would begin to fail and require repair or replacement.

Damage-State Medians for drift-sensitive nonstructural components must be converted from drift ratio to spectral displacement in a manner similar to that used for the structural system. Inter-story drift ratios for each damage state are converted to the corresponding amount of spectral displacement using the modal factor, α_2, and other terms:

$$\mathbf{S}_{\mathbf{d,ds}} = F_{\phi P,ds} \cdot \Delta_{ds} \cdot H_R \cdot \alpha_2 \tag{6-2}$$

Where:

Where:	$\mathbf{S}_{\mathbf{d,ds}}$	=	Median spectral displacement value of damage state, ds (inches)
	$F_{\phi P,ds}$	=	Factor relating average inter-story drift to the drift ratio of the component at damage state, ds, as defined by Equation (6-3)
	Δ_{ds}	=	Component drift ratio corresponding to threshold of damage state, ds, determined by user (consistent with the generic values of Table 6.3)
	H_R	=	Height of building at the roof level (inches)
	α_2	=	Pushover modal factor from Equation (5-2).

The factor, $F_{\phi P,ds}$, is used to relate average inter-story drift to maximum inter-story drift to account for the effects of an uneven distribution of drift over the height of the building. Uneven distribution of drift causes damage to occur at certain stories sooner than at other stories. The factor, $F_{\phi P,ds}$, is based on both the shape of the pushover mode and damage-state loss ratio:

$$F_{\varphi P,ds} = \frac{\varphi_{R,P}(1 - NSD_{ds})}{H_R \cdot \Delta_{max,P}} - NSD_{ds} \qquad (6\text{-}3)$$

Where: $\phi_{R,P}$ = Roof displacement of the pushover mode for damage state, ds (inches)

NSD_{ds} = Nonstructural drift-sensitive component loss ratio of damage state, ds (expressed as a fraction)

H_R = Height of building at the roof level (inches)

$\Delta_{max,P}$ = Maximum inter-story drift ratio (considering torsion) over the height of the building corresponding to the roof displacement, $\phi_{R,P}$.

The factor, $F_{\phi P,ds}$, makes use of the results of the pushover analysis to better predict localized damage and loss for buildings that have a structural irregularity (e.g., soft story). When drift is uniformly distributed over building height, the value of the factor is equal 1.0. When drift is not uniformly distributed over building height, the factor reduces median values to reflect the lower thresholds of damage associated with accentuated drift of critical stories. The factor varies with the loss ratio of the damage state, effectively reducing the influence of localized damage on the more extensive states of damage (i.e., factor is 1.0 for Complete Damage).

Damage-State Medians for nonstructural acceleration-sensitive components (and contents) are developed in terms of peak floor acceleration. In general, medians expressed in terms of spectral acceleration are taken as equal to peak floor acceleration values since spectral acceleration (obtained by the intersection of pushover curve and spectral demand) is assumed to represent peak floor acceleration of a typical upper floor of the building. Demand on components (and contents) at ground level is based directly on peak ground acceleration and is also assumed to represent peak (ground) floor acceleration. The trivial equation summarizing conversion peak floor acceleration of each damage state to the corresponding amount of spectral acceleration is:

$$\mathbf{S}_{\mathbf{a,ds}} = A_{max,ds} \qquad (6\text{-}4)$$

Where: $\mathbf{S}_{\mathbf{a,ds}}$ = Median spectral acceleration value of damage state, ds (units of g)

$A_{max,ds}$ = Peak floor acceleration of the threshold of damage state, ds (units of g) determined by user or based on generic values of Table 6.3.

The assumption that peak floor acceleration is the same as spectral acceleration demand ignores higher-mode shaking effects (not included in the pushover analysis) and the uneven distribution of floor acceleration over building height. Higher-mode effects can significantly increase upper-floor accelerations, although they may not cause failure of systems that have some ductility. Users concerned about higher-mode response could reduce median values by a factor inversely proportional to the increase in (damaging) floor acceleration associated with higher-mode response.

Peak floor acceleration will vary over the height of the building, typically with the largest accelerations at the roof. The intersection of the pushover and demand spectrum corresponds to building response at a floor elevation of about α_2 x H_R. Users concerned that this location is not representative of a typical upper floor of nonstructural acceleration-sensitive components (e.g., all the equipment is on the roof) could modify median values based on the location of the components and the shape of the pushover mode. Such modification would have little effect on the prediction of damage for most buildings with well distributed nonstructural systems.

6.3 Development of Damage-State Variability

Lognormal standard deviation (**Beta**) values describe the total variability of fragility-curve damage states. Three primary sources contribute to the total variability of any given state, namely, the variability associated with the capacity curve, β_C, the variability associated with the demand spectrum, β_D, and the variability associated with the discrete threshold of each damage state, $\beta_{T,ds}$, as described in Equation (6-5):

$$\boldsymbol{\beta}_{\mathbf{ds}} = \sqrt{\left(\mathrm{CONV}[\beta_C, \beta_D]\right)^2 + \left(\beta_{T,ds}\right)^2} \tag{6-5}$$

Where: $\boldsymbol{\beta}_{\mathbf{ds}}$ is the lognormal standard deviation parameter that describes the total variability of damage state, ds,

β_C is the lognormal standard deviation parameter that describes the variability of the capacity curve,

β_D is the lognormal standard deviation parameter that describes the variability of the demand spectrum (values of $\beta_D = 0.45$ at short periods and $\beta_D = 0.50$ at long periods were used to develop Tables 6.5 – 6.7),

$\beta_{T,ds}$ is the lognormal standard deviation parameter that describes the variability of the threshold of damage state, ds.

Since the demand spectrum is dependent on building capacity, a convolution process is required to combine their respective contributions to total variability. This is referred to as “CONV” in Equation (6-5). The third contributor to total variability, $\beta_{T,ds}$, is assumed mutually independent of the first two variables and is combined with the results of the CONV process using the square-root-sum-of-the squares (SRSS) method. Additional background on the calculation of **Damage-State Beta’s** is provided in the *Hazus-MH 2.1 Technical Manual* and the *Earthquake Spectra* paper “Development of Building Damage Functions for Earthquake loss Estimation” [Kircher et al., 1997a].

The variability of the demand spectrum (i.e., variability of ground shaking) is a key parameter in the calculation of damage-state variability. The values of demand variability, $\beta_D = 0.45$ at short periods and $\beta_D = 0.50$ at long periods, are the same as those used to calculate the default fragility curves of the *Hazus-MH 2.1 Technical Manual*. These values are consistent with the variability (e.g., dispersion factor) of ground shaking attenuation functions used by *Hazus* to predict response spectra for large-magnitude events in the Western United States (WUS). It may be noted that if there were no variability of demand (response spectrum is known exactly), then Equation (6-5) would become:

$$\beta_{ds} = \sqrt{(\beta_C)^2 + (\beta_{T,ds})^2} \tag{6-6}$$

This equation provides a lower-bound on the damage-state variability appropriate for use in probabilistic calculations of damage and loss that are based on the integration of the fragility with hazard functions that have already incorporated ground shaking variability in the hazard calculations. Similarly, Equation (6-6) also provides a lower-bound on damage-state variability for calculation of damage and loss using a response spectrum that is reasonably well known (i.e., response spectrum of recorded ground shaking). Arguably, there would always be some amount variability (uncertainty) in ground shaking demand, β_D, but such can be ignored in the calculation of total damage-state variability, β_{ds}, when substantially less than both capacity curve variability, β_C, and damage-state threshold variability, $\beta_{T,ds}$.

The convolution process involves a complex numerical calculation that would be very difficult for most users to perform. To avoid this difficulty, sets of pre-calculated values of **Damage-State Beta's** have been compiled in Tables 6.5 through 6.7 from which users may select appropriate values of variability for the structural system, nonstructural drift-sensitive components and nonstructural acceleration-sensitive components. The Beta values of these tables are a function of the following building characteristics and criteria:

- Building Height Group - Low-Rise Buildings (Table 6.5), Mid-Rise Buildings (Table 6.6) and High-Rise Buildings (Table 6.7)
- Post-Yield Degradation of the Structural System – Minor, Major and Extreme Degradation
- Damage-State Threshold Variability – Small, Moderate or Large Variability
- Capacity Curve Variability – Very Small, Small, Moderate or Large Variability.

The Beta values of the tables are applicable to all model building types. For example, a low-rise concrete-frame building (C1L) would have the same set of Beta's as a low-rise braced steel frame building (S2L), provided the two buildings have the same amount of capacity curve and damage-state threshold variability, and the same amount of post-yield degradation of the structural system.

Post-yield degradation of the structural system is defined by a Kappa factor, which is an direct measure of the effects of seismic design level and construction quality on the variability of response. Buildings that are seismically designed and/or have superior construction are less likely to degrade during post-yield earthquake shaking, and therefore have more predictable response, than buildings that are not seismically designed and/or have inferior construction.

To select a set of building-specific **Damage-State Beta's** (i.e., a structural Beta, a nonstructural drift-sensitive Beta and a nonstructural acceleration-sensitive Beta), users must first determine the building height group that best represents the specific building of interest. The height groups are defined by the same criteria as those used by *Hazus* to define generic building types. For example, a 5-story, reinforced concrete building would be classified as a mid-rise building as per the height criteria of Table 2-1.

Tables 6-5 through 6-7 (referred to as the Beta tables) provide recommended sets of **Damage-State Beta's** for each of the three building height groups, respectively. In each of these tables, the Beta's are based on 36 possible combinations of capacity curve variability, damage threshold variability and the amount of post-yield degradation expected for the structural system.

Estimation of structural system degradation (minimum or maximum) is made on the basis of **Kappa** factors suggested by Table 5.2 (Section 5.3.3) and the degree of post-yield response expected for the damage state of interest. **Kappa** factors decrease with increase in response level (and damage). Slight damage corresponds to response between ½ yield and full yield; Moderate damage to response at or just beyond yield; and Extensive and Complete damage correspond to post-yield response for the duration of scenario earthquake shaking. Beta values are given in Tables 6-5 through 6-7 for $\kappa \geq 0.9$ (minor degradation), $\kappa = 0.5$ (major degradation) and $\kappa \leq 0.1$ (extreme degradation) of the structural system; and linear interpolation may used to establish Beta's for other values of the **Kappa** factor.

Estimation of the variability of the capacity curve (β_C) and the variability of the threshold of the damage state ($\beta_{T,ds}$) must be made by users on a judgmental basis (with some guidance provided herein). To assist the user, the Beta tables express capacity curve and damage threshold variability qualitatively (e.g., Small Variability) and in term of the numerical value used to develop the Beta's in the CONV process. Numerical values of variability (β_C and $\beta_{T,ds}$) are lognormal standard deviation parameters and may be used, as illustrated in Figure 6.2, to construct the distribution of capacity or damage threshold that they represent.

The variability of capacity curves and the damage-state thresholds are influenced by:

- Uncertainty in capacity curve properties and the thresholds of damage states, and
- Building population (i.e., individual building or group of buildings).

Relatively low variability of damage states would be expected for an individual building with well known properties (e.g., complete set of as-built drawings, material test data, etc.) and whose performance and failure modes are known with confidence. The taller the building the greater the variability in damage state due to uncertainty in the prediction of response and damage using pushover analysis. Relatively high variability of damage states would be expected for a group of buildings whose properties are not well known and for which the user has low confidence in the results (of pushover analysis) that represent performance and failure modes of all buildings of the group. The latter case essentially describes the original development of damage-state fragility curves for generic model building that were based on capacity variability, $\beta_C = 0.3$, and damage-state threshold variability, $\beta_{T,ds} = 0.3$ (Structure), $\beta_{T,ds} = 0.5$ (NSD) and $\beta_{T,ds} = 0.6$ (NSA). The generic model building types represent large populations of buildings for which properties are not well known.

Building System[2]	Post-Yield Degradation of Structural System[3]								
	Minor Degradation (κ >= 0.9)			Major Degradation (κ = 0.5)			Extreme Degradation (κ <= 0.1)		
	Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)		
	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)
Structural Systems with Very Small Capacity Curve Variability[5] ($\beta_C = 0.1$)									
Structure	0.70	0.80	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSD	0.65	0.75	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Small Capacity Curve Variability[5] ($\beta_C = 0.2$)									
Structure	0.70	0.80	0.90	0.85	0.90	1.00	0.95	1.05	1.15
NSD	0.70	0.75	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Moderate Capacity Curve Variability[5] ($\beta_C = 0.3$)									
Structure	0.75	0.80	0.95	0.85	0.95	1.05	1.00	1.05	1.15
NSD	0.70	0.80	0.90	0.85	0.95	1.05	1.00	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Large Capacity Curve Variability[5] ($\beta_C = 0.4$)									
Structure	0.80	0.85	0.95	0.90	1.00	1.10	1.05	1.10	1.20
NSD	0.75	0.85	0.95	0.90	1.00	1.05	1.00	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65

Table 6.5. Low-Rise Building Fragility Beta's

Building System[2]	Post-Yield Degradation of Structural System[3]								
	Minor Degradation (κ >= 0.9)			Major Degradation (κ = 0.5)			Extreme Degradation (κ <= 0.1)		
	Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)		
	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)
Structural Systems with Very Small Capacity Curve Variability[5] (β_C = 0.1)									
Structure	0.70	0.80	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSD	0.65	0.75	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Small Capacity Curve Variability[5] (β_C = 0.2)									
Structure	0.70	0.80	0.90	0.85	0.90	1.00	0.95	1.05	1.15
NSD	0.70	0.75	0.90	0.85	0.90	1.00	0.95	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Moderate Capacity Curve Variability[5] (β_C = 0.3)									
Structure	0.75	0.80	0.95	0.85	0.95	1.05	1.00	1.05	1.15
NSD	0.70	0.80	0.90	0.85	0.95	1.05	1.00	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Large Capacity Curve Variability[5] (β_C = 0.4)									
Structure	0.80	0.85	0.95	0.90	1.00	1.10	1.05	1.10	1.20
NSD	0.75	0.85	0.95	0.90	1.00	1.05	1.00	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65

1. Building Systems include the Structure, Nonstructural Drift-Sensitive Components (NSD) and Nonstructural Acceleration-Sensitive (NSA) components.

Table 6.6. Mid-Rise Building Fragility Beta's

Building System[2]	Post-Yield Degradation of Structural System[3]								
	Minor Degradation (κ >= 0.9)			Major Degradation (κ = 0.5)			Extreme Degradation (κ <= 0.1)		
	Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)			Damage Variability[4] ($\beta_{T,ds}$)		
	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)	Small (0.2)	Mod. (0.4)	Large (0.6)
Structural Systems with Very Small Capacity Curve Variability[5] (β_C = 0.1)									
Structure	0.60	0.70	0.80	0.70	0.80	0.90	0.85	0.95	1.05
NSD	0.60	0.70	0.80	0.80	0.85	0.95	0.90	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Small Capacity Curve Variability[5] (β_C = 0.2)									
Structure	0.65	0.75	0.85	0.75	0.85	0.95	0.95	1.00	1.10
NSD	0.65	0.70	0.85	0.80	0.85	1.00	0.95	1.00	1.10
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Moderate Capacity Curve Variability[5] (β_C = 0.3)									
Structure	0.65	0.75	0.85	0.80	0.85	0.95	0.95	1.00	1.10
NSD	0.65	0.75	0.85	0.80	0.90	1.00	0.95	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
Structural Systems with Large Capacity Curve Variability[5] (β_C = 0.4)									
Structure	0.70	0.75	0.90	0.80	0.90	1.00	1.00	1.05	1.15
NSD	0.70	0.75	0.90	0.85	0.90	1.00	1.00	1.05	1.15
NSA	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65

1. Building Systems include the Structure, Nonstructural Drift-Sensitive Components (NSD) and Nonstructural Acceleration-Sensitive (NSA) components.

Table 6.7. High-Rise Building Fragility Beta's

<table>
<tr><td rowspan="4">Building System[2]</td><td colspan="9">Post-Yield Degradation of Structural System[3]</td></tr>
<tr><td colspan="3">Minor Degradation (κ >= 0.9)</td><td colspan="3">Major Degradation (κ = 0.5)</td><td colspan="3">Extreme Degradation (κ <= 0.1)</td></tr>
<tr><td colspan="3">Damage Variability[4] ($\beta_{T,ds}$)</td><td colspan="3">Damage Variability[4] ($\beta_{T,ds}$)</td><td colspan="3">Damage Variability[4] ($\beta_{T,ds}$)</td></tr>
<tr><td>Small (0.2)</td><td>Mod. (0.4)</td><td>Large (0.6)</td><td>Small (0.2)</td><td>Mod. (0.4)</td><td>Large (0.6)</td><td>Small (0.2)</td><td>Mod. (0.4)</td><td>Large (0.6)</td></tr>
<tr><td colspan="10">Structural Systems with Very Small Capacity Curve Variability[5] (β_C = 0.1)</td></tr>
<tr><td>Structure</td><td>0.55</td><td>0.65</td><td>0.80</td><td>0.65</td><td>0.75</td><td>0.85</td><td>0.80</td><td>0.90</td><td>1.00</td></tr>
<tr><td>NSD</td><td>0.55</td><td>0.65</td><td>0.80</td><td>0.75</td><td>0.80</td><td>0.95</td><td>0.90</td><td>0.95</td><td>1.05</td></tr>
<tr><td>NSA</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td></tr>
<tr><td colspan="10">Structural Systems with Small Capacity Curve Variability[5] (β_C = 0.2)</td></tr>
<tr><td>Structure</td><td>0.60</td><td>0.65</td><td>0.80</td><td>0.70</td><td>0.80</td><td>0.90</td><td>0.90</td><td>0.95</td><td>1.05</td></tr>
<tr><td>NSD</td><td>0.60</td><td>0.70</td><td>0.80</td><td>0.75</td><td>0.85</td><td>0.95</td><td>0.95</td><td>1.00</td><td>1.10</td></tr>
<tr><td>NSA</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td></tr>
<tr><td colspan="10">Structural Systems with Moderate Capacity Curve Variability[5] (β_C = 0.3)</td></tr>
<tr><td>Structure</td><td>0.60</td><td>0.70</td><td>0.80</td><td>0.70</td><td>0.80</td><td>0.90</td><td>0.95</td><td>1.00</td><td>1.10</td></tr>
<tr><td>NSD</td><td>0.60</td><td>0.70</td><td>0.85</td><td>0.80</td><td>0.85</td><td>0.95</td><td>0.95</td><td>1.05</td><td>1.15</td></tr>
<tr><td>NSA</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td></tr>
<tr><td colspan="10">Structural Systems with Large Capacity Curve Variability[5] (β_C = 0.4)</td></tr>
<tr><td>Structure</td><td>0.60</td><td>0.70</td><td>0.85</td><td>0.75</td><td>0.80</td><td>0.95</td><td>0.95</td><td>1.00</td><td>1.10</td></tr>
<tr><td>NSD</td><td>0.60</td><td>0.70</td><td>0.85</td><td>0.80</td><td>0.90</td><td>1.00</td><td>1.00</td><td>1.05</td><td>1.15</td></tr>
<tr><td>NSA</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td><td>0.35</td><td>0.50</td><td>0.65</td></tr>
</table>

1. Building Systems include the Structure, Nonstructural Drift-Sensitive Components (NSD) and Nonstructural Acceleration-Sensitive (NSA) components.

SECTION 7

DEVELOPMENT OF LOSS FUNCTIONS

7.1 Building Loss Criteria

This section guides users in the development of loss functions that are used by Advanced Engineering Building Module (AEBM) to calculate building losses as a function of damage-state probability (i.e., building fragility). It is essential that this section be coordinated with the development of fragility parameters in Section 6 for those parameters that share common assumptions (e.g., repair/replacement cost assumed for damage states).

Building loss data may be thought of as falling into either one or the other of two basic groups:

- Non-Damage-Related – Loss data related to building occupancy or economic value including the number of building occupants and the replacement cost of the building and contents
- Damage-Related – Loss data derived from and related to the damage states such as the cost of earthquake repair and time required for clean up and repair.

Hazus default inventory data assume a certain size, square footage, replacement value and number of occupants for each building occupancy and type that may be very different from that of the specific building of interest. *Hazus* default inventory data should not be used for building-specific applications without verification. Typically, owners would be able to provide and/or verify non-damage-related data for specific buildings.

Development of damage-related loss data require users to either calculate or estimate different types of loss for the specific states of damage described by the pushover analysis. For development of casualty rates, users should consider how collapse failure could occur (e.g., local collapse, single-story collapse or "pancake " collapse of the whole building) and injure or kill building occupants. For development of direct economic loss rates, users should consider the process (scope of work and time required) to repair each state of damage (i.e., Slight, Moderate, Extensive and Complete) to the structural system, nonstructural components and contents of the building. Users may choose to use the default values of *Hazus* loss functions, but should always verify that the default values appear reasonable for the specific building of interest.

7.2 Direct Social Losses - Casualties

Hazus methods distinguish between "indoor" and "outdoor" casualties, the later referring to deaths and injuries to pedestrians (or people in cars, etc.) that are near the building at the time of the earthquake. The AEBM estimates deaths and injuries using "indoor" casualty rates and does not calculate "outdoor" casualties.

Hazus methods base "indoor" casualty rates solely on structural damage states and base collapse-related deaths solely on Complete structural damage. Some buildings may have Collapse failure of elements or components (e.g., out-of-plane failure of in-fill wall) prior to the building reaching a Complete state of damage. Some buildings may also have nonstructural components and equipment whose failure could cause injury and death of occupants. Additionally, casualties due to fire, release of hazardous materials, electrocution or other indirect effects of structural or nonstructural damage, are not included in *Hazus* casualty rates. For most buildings, these effects do not dominate earthquake casualties. Structural damage tends to dominate deaths and serious injuries, particularly when there is a significant probability of Complete structural damage.

The default rates of *Hazus* seem to produce reasonable estimates of casualties for large study regions composed of many buildings, but may significantly under-predict (or over-predict) casualties, in particular deaths, for an individual building. To better estimate deaths, users may choose to develop building-specific casualty rates for the Complete structural damage. The validity of building-specific rates is dependent on accurate prediction of collapse failure modes by pushover analysis, and the user's subjective evaluation of the relative likelihood of Collapse failure given the building is in the Complete state of damage. As described in Subsection 4.3.2**,** **Collapse Casualty Rates**, **P[S_i|COL]**, are conditional on the **Collapse Factor**, **P[COL|STR_5]**, where "STR_5" is the state of Complete structural damage. Definitions of casualty severity are given in Table 7.1.

Table 7.1. *Hazus* Casualty Classification Scale

Casualty Level	Casualty Description
Severity 1	Injuries requiring basic medical aid, but without hospitalization (treat and release)
Severity 2	Injuries requiring medical attention and hospitalization, but not considered to be life-threatening
Severity 3	Casualties that include entrapment and require expeditious rescue and medical treatment to avoid death
Severity 4	Immediate deaths

Casualty rates given collapse, **P[S_i|COL]**, apply only to occupants in the portion of the building that has actually collapsed. For most building types, the default values of *Hazus* assume that only 10 in every 100 occupants in the collapsed portion of the building would be killed immediately (Severity 4) and another 5 in every 100 occupants would be trapped and not survive without expeditious rescue and treatment (Severity 3). These values are based on a variety of generic building configurations and the assumption that even with collapse the vast majority of exposed occupants can crawl out of the structure. These values may be low by as much as a factor of 5 for evaluation of specific buildings that are expected to have "pancake" types of failure or could otherwise bury occupants under heavy building debris. Such failures would trap and kill a much larger fraction of occupants in the collapsed portion of the building, although most exposed occupants would still be expected to survive.

In cases where collapse failure is expected to crush or bury building occupants under heavy building debris (e.g., concrete or masonry material), users should modify the casualty rates, **P[S_i|COL]**. In such cases, casualty rates for Severity 3 and 4 should be increased by a factor ranging from 2 (for local collapse involving heavy debris) to 5 (for full pancake collapse of stories). The casualty rate for Severity 1 should also be adjusted downward as required for the sum of the casualty rates (and the implicit probability of no injury or death) to equal 1.0.

The Collapse Factor, $\mathbf{P[COL|STR_5]}$, is a probability that effectively defines the fraction of building occupants expected to be exposed to some type of collapse given that the building has reached the Complete state of damage. Default values of *Hazus* collapse rates range from a probability of 3% to 15% as summarized in Table 7.2.

Table 7.2. *Hazus* Collapse Rates for Generic-Building Types

Model Building Type	Collapse Rate
W1, W2, S1H, S2H, S3, S4H, S5H and MH	3%
S1M, S2M, S4M, S5M, C1H, C2H and RM2H	5%
S1L, S2L, S4L and S5L	8%
C1M, C2M, C3H, PC2H, RM1M and RM2M	10%
C1L, C2L, C3M, PC2M, RM1L and RM2L	13%
C3L, PC1, PC2L, URML and URMM	15%

The expected fraction of occupants exposed to Collapse may be thought of the "weighted" sum of the individual fractions associated with each different collapse failure mode. The fraction of occupants exposed to a given Collapse failure mode is calculated by multiplying the likelihood of that mode of Collapse failure times the number of occupants that would be exposed to such failure. Following this logic, the Collapse Factor, $\mathbf{P[COL|STR_5]}$, is expressed by Equation (7-1):

$$\mathbf{P}\left[\mathbf{COL} \mid \mathbf{STR}_5\right] = \sum_i \mathrm{P}\left[\mathrm{C}_i\right] \cdot \mathrm{F}_{\mathrm{BO},i} \qquad (7\text{-}1)$$

Where: $P[C_i]$ = Probability of Collapse failure mode i

$F_{BO,i}$ = Fraction of building occupants exposed to Collapse failure mode i.

While there could be many types of Collapse failure modes (given Complete structural damage has occurred), the user may wish to consider the following four general types:

- C_0 No Collapse – Building is a complete loss, but does not threaten life safety
- C_L Local Collapse – Localized collapse of building elements or components (e.g., out-of-plane collapse of infill walls)
- C_S Story Collapse – Collapse of an individual story or portion thereof (e.g., soft-story)
- C_G Global Collapse – Collapse over multiple stories (e.g., "pancake" collapse).

For each of these four possible types of Collapse failure, the user would estimate both the probability of the failure mode, $P[C_i]$, and the fraction of exposed occupants, $F_{BO,i}$. For example, the probability of various failure modes and fraction of exposed occupants of a mid-rise unreinforced masonry building (URMM) might be estimated as follows:

- $P[C_0] = 0$ $F_{BO,i} = 0.0$ Building is assumed to have sustained some amount of collapse, ($P[C_O] = 0$), since at least some local (e.g. wall) failure will have occurred if the building has reached the Complete state of damage
- $P[C_L] = 0.5$ $F_{BO,i} = 0.1$ Building is assumed to have a 50% probability of localized failure of walls; but localized failure would only expose about 10% of building occupants to collapse
- $P[C_S] = 0.5$ $F_{BO,i} = 0.25$ Building is assumed to have a 50% probability of single-story collapse; a single-story failure would expose about 20% of building occupants to collapse (i.e., for a 5-story building)
- $P[C_G] = 0.0$ $F_{BO,i} = 1.0$ Building is assumed to have no significant probability of total building collapse that would expose all building occupants to collapse.

The calculation of the Collapse Factor, **$P[COL|STR_5]$**, for this example is shown in Equation (7-2):

$$\mathbf{P}\left[\mathbf{COL} \mid \mathbf{STR_5}\right] = 0.0 \times 0.0 + 0.5 \times 0.1 + 0.5 \times 0.2 + 0.0 \times 1.0 = 15\% \qquad (7\text{-}2)$$

In this case, the calculated value of the Collapse Factor, 15%, is found to be the same as the *Hazus* default value for a generic URMM building given in Table 7.2. This probability value is based on two equally likely failure modes, involving either local collapse of a wall or collapse of a single story, without significant likelihood of total building collapse. The Collapse Factor would be substantially greater than 15% if the building was deemed to have a significant probability of total collapse.

7.3 Direct Economic Losses

Direct economic losses include costs of building repair (or replacement) of structural and nonstructural systems, contents and business inventory. Direct economic losses also include costs due to loss of building function. Users may choose to use the default values of *Hazus* loss functions, but should always verify that the default values appear reasonable for damage states of the specific building of interest. When developing building-specific values, or simply verifying the appropriateness of default values, users should carefully think through the process, work and time that would be required to repair Slight, Moderate, Extensive and Complete damage to elements and components as described by pushover analysis.

Some consideration should be given to prevailing codes and ordinances that would govern the repair work.. Do prevailing regulations require strengthening as well as repair? Is the building of historical significance, or otherwise have special conditions that could influence repair? Earthquake repair and strengthening of historical buildings can be extremely expensive (due to preservation of historical features), even though the damage triggering such repair may be relatively modest. For example, the historical San Francisco City Hall sustained only Moderate damage due to the 1989 Loma Prieta earthquake, but the cost of repair and strengthening the building was many times the cost of a new building of comparable size. The default loss ratio of 10% for Moderate damage would not be appropriate in this case and would not produce an accurate estimate of the direct economic loss that actually occurred. However, if only Slight damage had occurred (e.g., due to a lower level of ground shaking), then damage would likely have not triggered seismic retrofit and post-earthquake clean-up efforts would have cost only a small fraction of total building value (more like the 2% default loss ratio for Slight damage).

The extraordinary cost of repair of the San Francisco City Hall after the 1989 Loma Prieta earthquake (over $100 million) would be difficult to estimate using *Hazus* methods, unless replacement value also included additional value due to the historical significance and importance of the building (and the large amount of available relief funding). As discussed in the *Hazus-MH 2.1 Technical Manual*, replacement value is the preferred measure of economic loss, although other measures could be used, such as loss of market value. Market value would, in general, produce entirely different loss estimates. For example, an older building of no special importance or historical significance is to be vacated and completely renovated, but instead an earthquake occurs and destroys the structure. Should economic loss be based on the replacement value (e.g., cost of a new building of comparable size and function), the near zero value of the existing building, or on the market value of the building (which would also include value of the land)? These types of question are crucial to the estimation of economic loss, but are beyond the scope of this manual. It is assumed that building-specific economic loss functions will be based on repair and replacement value of the building and contents, consistent with *Hazus* methods for generic building types.

7.3.1 Repair Costs

Repair cost rates define expected dollar costs (e.g., as fraction of building value) that would be required to repair or replace building damage. Repair and replacement costs are required for each state of damage of the structural system, nonstructural drift-sensitive components, nonstructural acceleration-sensitive components and building contents and business inventory. *Hazus* default values of repair and replacement costs are different for each occupancy, and estimation of structural costs is also different for each model building type.

Development of building-specific cost factors involves two basic components:

- Determining the total replacement cost of building systems, contents and business inventory
- Determining the appropriate fractions (loss ratios) of the total replacement cost corresponding to each damage state.

It is expected that the user (e.g., with owner assistance) would be able to develop an estimate of the total replacement cost of building systems (and contents and business inventory) and would not need to rely on the default vales of *Hazus*. The total replacement cost of the building should be divided into the cost of the structural system, the cost of nonstructural drift-sensitive components and the cost of nonstructural acceleration-sensitive components. For reference,

Table 2.4 lists typical drift-sensitive and acceleration-sensitive components of nonstructural systems. Table 7.3 summarizes the fractional costs of buildings systems assumed by *Hazus* for some common combinations of occupancy and building type. Also shown in Table 7.3 are the percentages of total nonstructural cost associated with drift-sensitive and acceleration-sensitive components, respectively.

Table 7.3. Fractional Cost of Structural and Nonstructural Systems of *Hazus* Generic Building Types and Occupancies

Common Combinations of Occupancy and Building Type (Occupancy Group)	Fraction of Total Building Cost		
	Structural System	Nonstructural Systems (Percent of Total Nonstructural Cost)	
		Drift-Sensitive	Accel.-Sensitive
Single-Family Residences - RES1/W1 (All Single-Family Residences)	0.25	0.49 (65%)	0.26 (35%)
Multi-Family Residences – RES3/W1 (All Non-Single-Family Residences)	0.18	0.41 (50%)	0.41 (50%)
Retail Commercial – COM1/S1M (All Commercial Buildings)	0.38	0.25 (40%)	0.37 (60%)
Light Industrial – IND2/PC1 (All Industrial Buildings)	0.27	0.11 (15%)	0.62 (85%)

Hazus default values of direct economic loss for structural and nonstructural systems are based on the following assumptions of the loss ratio corresponding to each state of damage:

- Slight damage would be a loss of 2% of building's replacement cost
- Moderate damage would be a loss 10% of the building's replacement cost
- Extensive damage would be a loss of 50% of the building's replacement cost
- Complete damage would be a loss of 100% of the building's replacement cost.

As discussed previously, the default values of loss ratio should not be used to develop building-specific loss functions, unless the user has used the same values to guide the development of damage-state medians (Section 6.2).

Hazus assumes contents loss ratios to be one-half of the default loss ratios of the building on the basis that one-half of building contents are not vulnerable to ground shaking and could be salvaged even if the building were severely damaged. Building-specific contents damage (loss ratios), $\mathbf{CD_{ds}}$, should be based on an appropriate fraction (e.g., one-half) of the loss ratios of acceleration-sensitive nonstructural components.

7.3.2 <u>Loss of Function</u>

Repair time, recovery time and service interruption multipliers do not affect the calculation of capital stock losses (e.g., repair/replacement costs), but significantly influence income-related losses, such as relocation, wages and rental income losses. Users should develop building-specific values for repair time based on the scope of repair/replacement work estimated for each damage state. Proportional changes to recovery time should also be made, if building-specific repair times are used in lieu of *Hazus* default values. In general, users would be expected to use the default values of service interruption multipliers to determine "loss of function" time for most building-specific applications.

SECTION 8

EXAMPLE ESTIMATION OF BUILDING DAMAGE AND LOSS USING THE AEBM

8.1 Background

This section demonstrates building-specific methods by developing damage and loss parameters for an individual building (before and after seismic upgrade), and by implementing these parameters in the AEBM of the *Hazus-MH 2.1 Software* to estimate losses for a scenario earthquake. In this example, the AEBM illustrates the calculation of earthquake losses that could be used by engineers and building owners to evaluate the benefits of seismic rehabilitation.

The example building is the Headquarters of Los Angeles County Department of Public Works (LACDPW) located in Alhambra, California. The Los Angeles office of Black & Veatch has investigated seismic hazard mitigation for this building [Chen et al., 2001]. Their study included a site-specific hazard evaluation [Geomatrix, 1999], field investigations and laboratory testing of girder-column connections at the University of California at San Diego [Chi and Uang, 2000], development of several different schemes for seismic retrofit of the structural system and estimation of the costs of each scheme. Performance of the structural system was evaluated by detailed nonlinear pushover analyses of the original building and each retrofit scheme.

The Black & Veatch study provides the requisite engineering and ground shaking data for AEBM evaluation of damage and loss. A scenario earthquake is selected based on the findings of Geomatrix' evaluation of ground shaking hazard at the site. Performance of the structural system is based on the results of pushover analyses of the original building and for one of the retrofit alternatives (i.e., scheme to strengthen girder-column connections). Damage and losses due to the scenario earthquake are calculated using the pushover results and other data specific to the LACDPW Headquarters building.

Section 8.2 describes pertinent building data, including engineering (pushover) analysis results of the Black & Veatch study and site-specific hazard data of the Geomatrix study. Subsequent sections show how these data are used to develop input to the AEBM of the *Hazus-MH 2.1 Software*, including entry (or editing) of building-specific data in AEBM databases. Similar to the *Hazus-MH 2.1 User's Manual*, screen shots of AEBM windows and pull-down menus are included in the example to illustrate manipulation of the AEBM software. The *Hazus-MH 2.1 User's Manual* should be referred to for manipulation of other *Hazus* software modules (e.g., defining scenario earthquake hazard).

8.2 Example Building Data

8.2.1 LACDPW Headquarters Building

The LACDPW Headquarters building has twelve above-grade levels, a mezzanine between the ground and second floor, a mechanical penthouse, and a basement level. The facility was originally constructed in 1971 for Sears Company in accordance with the 1967 *Uniform Building Code* [ICBO, 1967].

The plan of the building for the above grade level is square in shape (167 ft. x 167 ft.). The floor to floor height is 14 ft.– 0 in., except that the 2nd floor is 27 ft.-5 in. above the ground floor. A photo of the DPW Building is included as Figure 8.1.

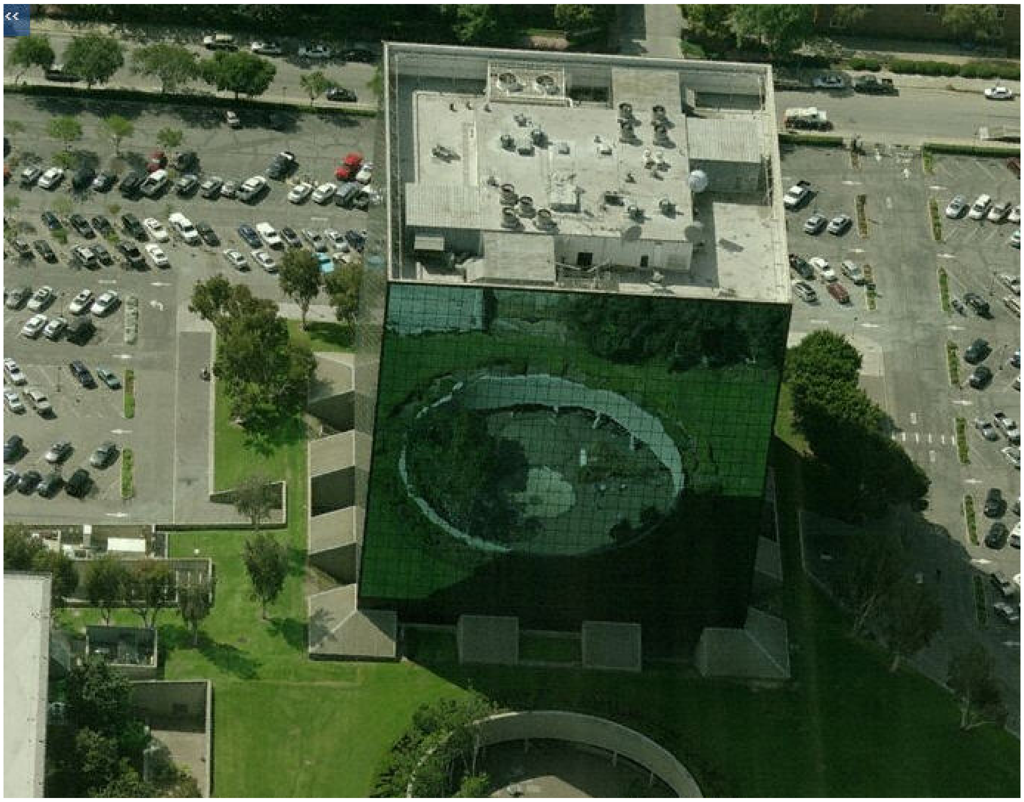


Figure 8.1. Photo of the DPW Building

8.2.2 Original Building (OB) Structure

The structural system of LACDPW Headquarters building features a perimeter welded steel moment frame (WSMF) with a bay width of 15 ft. and a story height of 14 ft. Figure 8.2 shows a typical floor framing plan and Figure 8.3 shows an elevation view of perimeter framing. A typical perimeter girder-column connection is shown in Figure 8.4. Welded moment connections also exist at sixteen interior gravity connections to increase the stiffness in east-west direction. The period of the OB is approximately 2.2 seconds. According to the as-built drawings, the building was designed for a lateral seismic force equal to 3.24% of the dead weight of the structure.

An inspection of the moment connections and a seismic evaluation of the building were conducted after the 1994 Northridge earthquake. The inspection did not reveal any damage due to the earthquake (i.e., ground shaking at the building site in Alhambra was relatively low). However, the inspection identified widespread poor-quality welds. As a result, the County (with funding provided in part by FEMA) has decided to seismically upgrade the building.

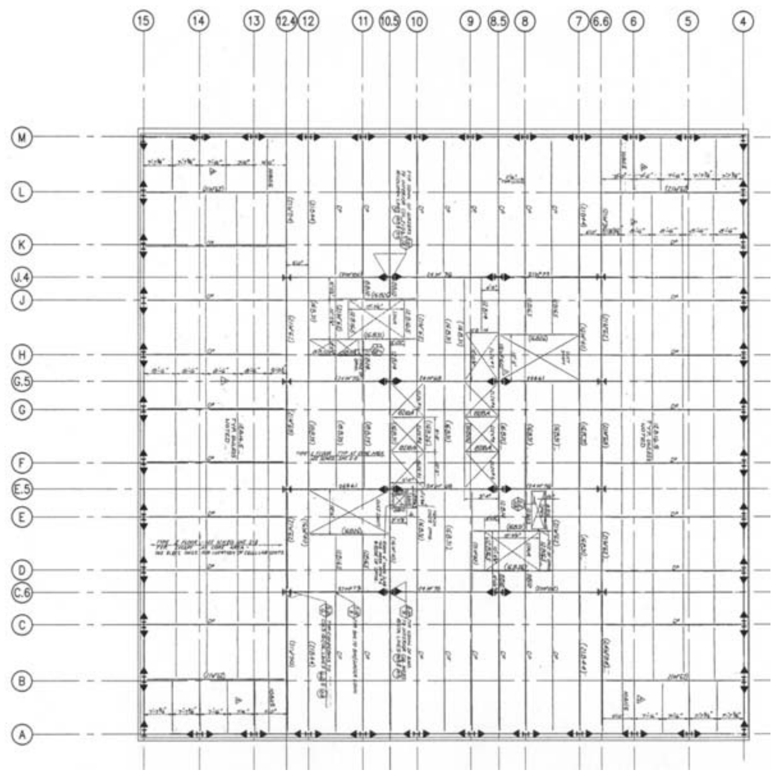


Figure 8.2. Typical Floor Framing of the DPW Building [Chen et al., 2001]

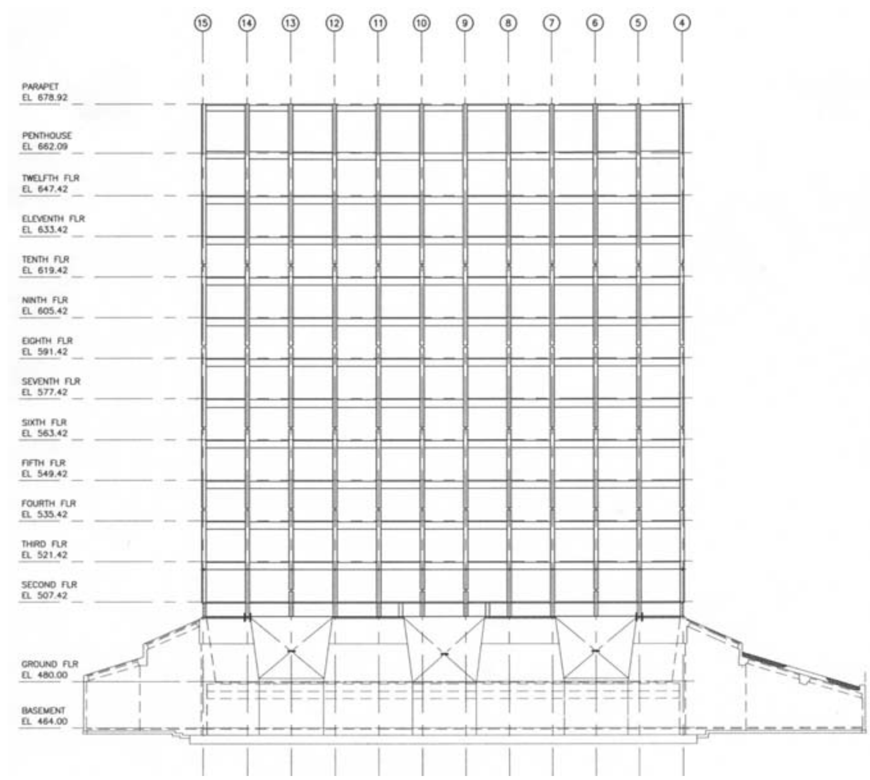


Figure 8.3. Elevation View at Perimeter of the DPW Building [Chen et al., 2001]

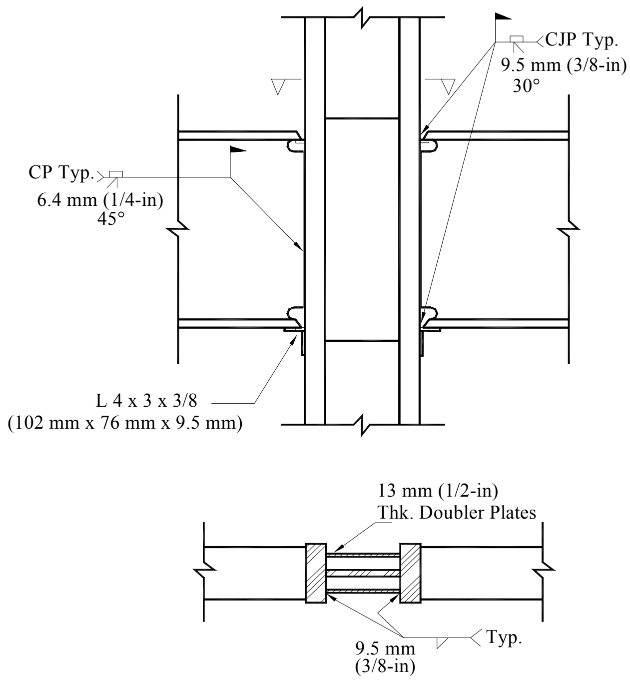


Figure 8.4. Typical Girder-Column Connection – Original Building [Chen et al., 2000]

8.2.3 Connection-Only (CO) Retrofit Scheme

The Connection-Only (CO) retrofit scheme consists of strengthening all the existing moment frame connections so that the plastic capacity of the girders can be developed, as envisioned in the original design. Many methods of connection repair were considered. The most cost-effective method was one that would not require removal of the concrete floor slab and modification to the top flange of the girder, or strengthening of the column to meet strong column-weak beam provisions.

The chosen repair was a haunch scheme, in which a diagonal plate is added to the bottom of the girder at the connection. Figure 8.5 shows a typical girder-column connection of the CO retrofit scheme, strengthened with haunches. This scheme proved to be the most cost effective, and was successfully tested at UCSD. The addition of haunches increases both the stiffness and strength of the structural system. The period of the CO retrofit scheme is approximately 1.8 seconds.

In addition to the connection repair, other strengthening measures are required to enable the frame to develop the plastic capacity of the girders. These include repairing all partial penetration welded column splices, adding side plates to the end column to increase its axial load carrying capacity, and strengthening the concrete base to carry the loads from the steel frame to the ground.

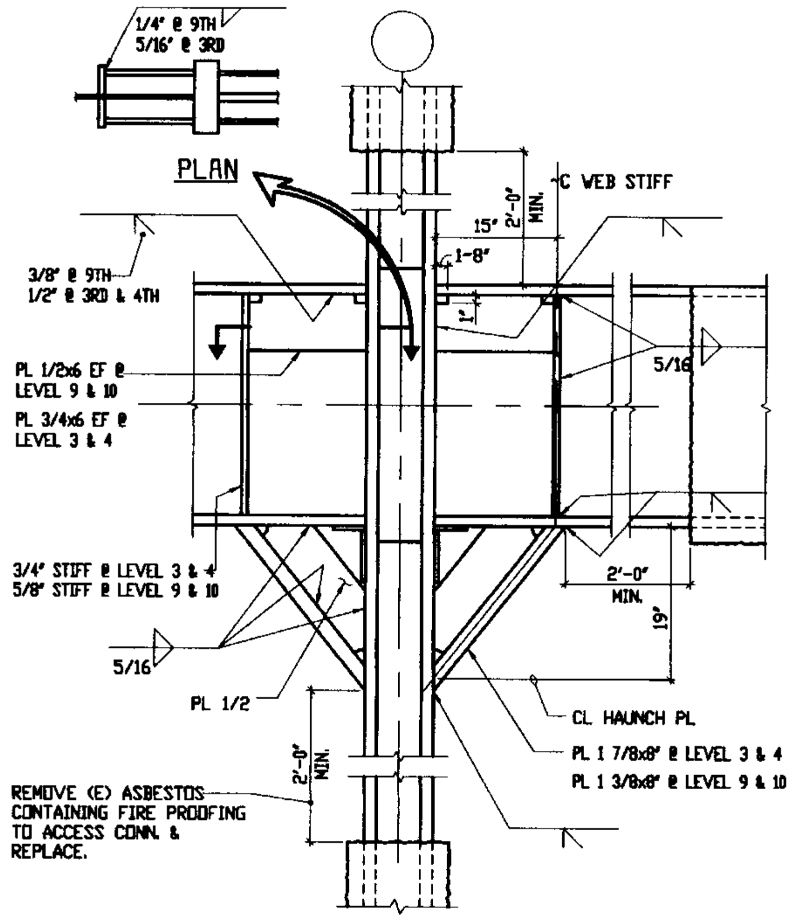


Figure 8.5. Typical Girder-Column Strengthening Detail [Chen et al., 2001]

8.2.4 Engineering Pushover Analyses

Seismic performance of the original building (OB) and the connection-only (CO) retrofit scheme were evaluated using the nonlinear static (pushover) analysis method of FEMA 273 [FEMA, 1997]. Due to the symmetry and regularity of the building's lateral force resisting system, the behavior of the steel frame and connections was analyzed using a two dimensional model of the west exterior frame.

The program used for analysis was SAP 2000 Nonlinear [CSI, 2000]. All steel girders and columns in the frame were modeled with the base of the columns considered as fixed at the top of the concrete wall below the second floor girder. Dead and live loads were applied to all members, and the effects of P-Delta were included by a dummy column with lumped masses at floor levels slaved to each floor. The pushover analysis was performed per the requirements of FEMA 273 using a code shaped distribution of lateral forces.

The girder-column connection was modeled to include the effects of shear deformation and shear yielding in the panel zone per the recommendations of FEMA 273. Test analyses were performed on the connection model to compare its behavior with the data from the full scale testing, and good conformance was observed.

8.2.5 Original Building (OB) Performance

Three different models of OB connections were created for the girder to column connection. The first two models were analyzed to establish upper-bound and lower-bound pushover response of the structure. The final model was compared to the bounding curves as a check of the results. In the upper-bound model, all connections were assumed to be fully ductile, with all connections behaving as elastic and plastic with no degradation in strength. For the lower-bound model, the bottom flanges of the girders in tension were assumed to crack at a stress of 33 ksi, and bottom flanges in compression and all top flanges were assumed to not crack. Once cracked, the girder end was modeled as a T-shaped section with the ability to perform in an inelastic manner. In the third analysis, the connections were modeled to match the strength and stiffness in both the elastic and inelastic regions as recorded in the UCSD testing. The pushover curves for the upper-bound and lower-bound models, as well as the model that using the backbone curve that match UCSD testing, are shown in Figure 8.6.

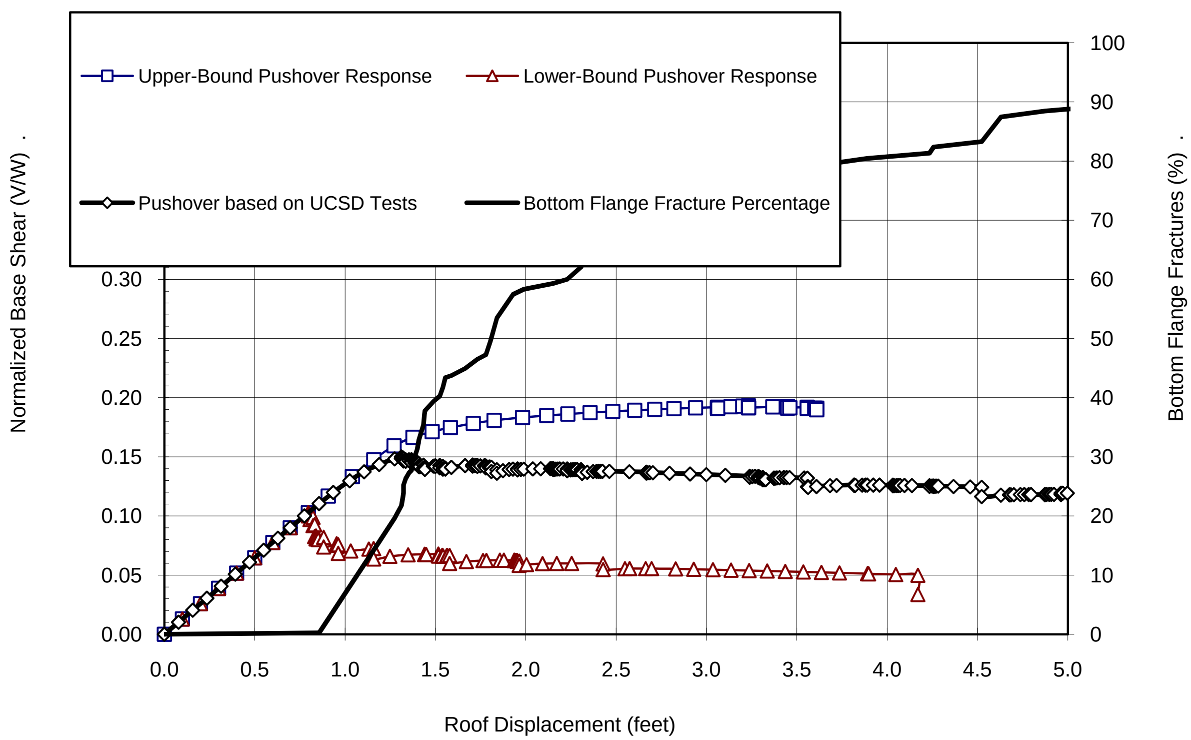


Figure 8.6. Pushover Curves and Connection Damage – Original Building

Using the data from the UCSD testing, the average plastic rotation at fracture for bottom flanges was computed as 0.0033 radians. Cracking of the girder bottom flange, defined as exceeding 0.0033 radians of plastic rotation, was first observed at a roof displacement of approximately 10 inches, with additional cracks occurring with additional displacement. The pushover curve indicates that the maximum strength of the building is developed at a roof displacement of 15.6 inches, with significant fractures developing at displacements of 12 to 22 inches. Based on a mean plastic rotation capacity of 0.0033 radians, the number of fractured (bottom flange) connections was calculated as a function of pushover displacement. The percentage of connections with bottom flange fractures is shown in Figure 8.6.

8.2.6 Connection-Only (CO) Retrofit Scheme Performance

Pushover analysis of the Connection-Only (CO) retrofit scheme was performed using the same SAP 2000 Nonlinear (frame) model as the OB with stiffer and stronger connections (see Figure 8.5). Strengthened connections were modeled to match UCSD test results, using a "backbone" curve similar to Figure 2-6 of FEMA 273. Strengthened connections do not fracture prematurely and inelastic behavior is due to primarily to yielding of girders (and columns). The pushover curve for the CO retrofit scheme is shown in Figure 8.7

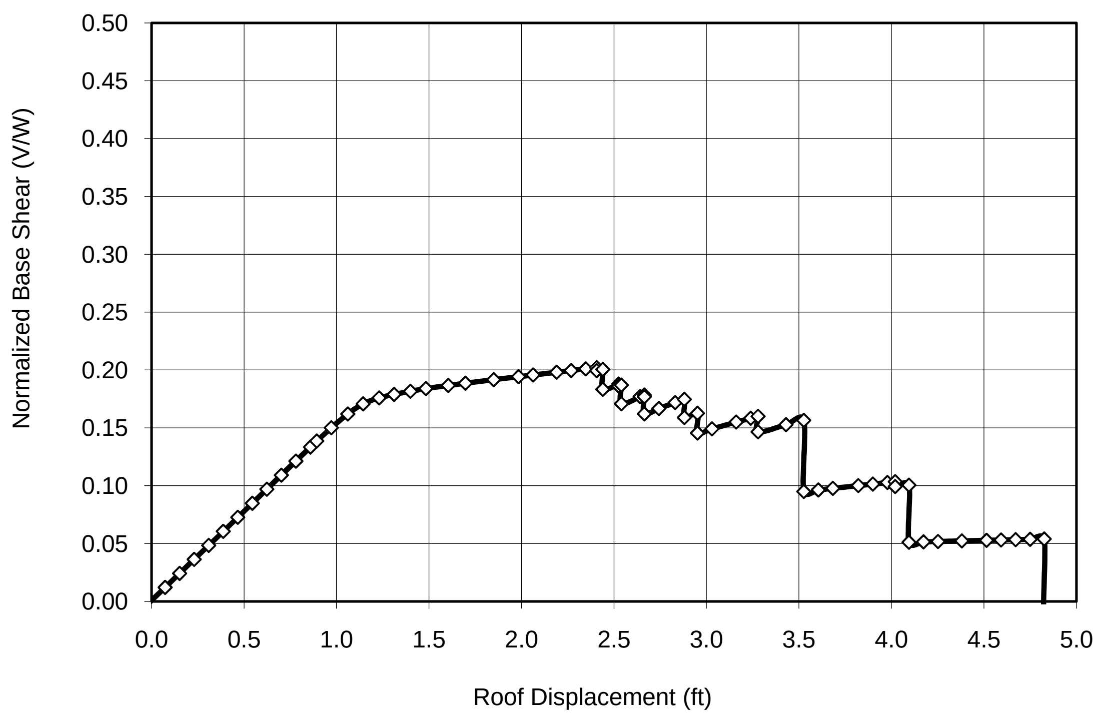


Figure 8.7. Pushover Curve – Connection-Only Retrofit Scheme

The pushover curve for the CO retrofit scheme indicates fully elastic behavior up to about a foot of roof displacement, after which girders (and columns) begin to yield. At about 2.5 feet of roof displacement, yielded girders begin loose strength (consistent with the shape of the "backbone" curve). Strength loss becomes significant at about 3.5 feet and full loss of strength occurs at about 5 feet of roof displacement.

8.2.7 Ground Shaking Hazard

Earthquake ground-shaking hazard at the LACDPW Headquarters building is dominated by faults in close proximity to the site. Most notably, these faults are: (1) the Raymond fault zone, which has a scarp mapped at the surface approximately 3¾ km (2.4 mile) north of the site and dips steeply to the north (away from the site); (2) the Verdugo-Eagle Rock fault zone, which is mapped as having a concealed surface trace approximately 4 km (2½ mile) north-northeast of the site and dips to the northeast (also away from the site); (3) the Sierra Madre fault zone, which is mapped as close as approximately 12 km (7½ mile) north-northeast of the site and dips to the north-northeast (away from the site, as well); and (4) the Hollywood-Santa Monica-Malibu Coast fault zone, situated about 12 km (7½ mile) to the west. As shown by the hazard curves in Figure 8.8, the Sierra Madre fault is the dominant contributor to short-period (PGA) and 1-second spectral response at the LACDPW Headquarters site.

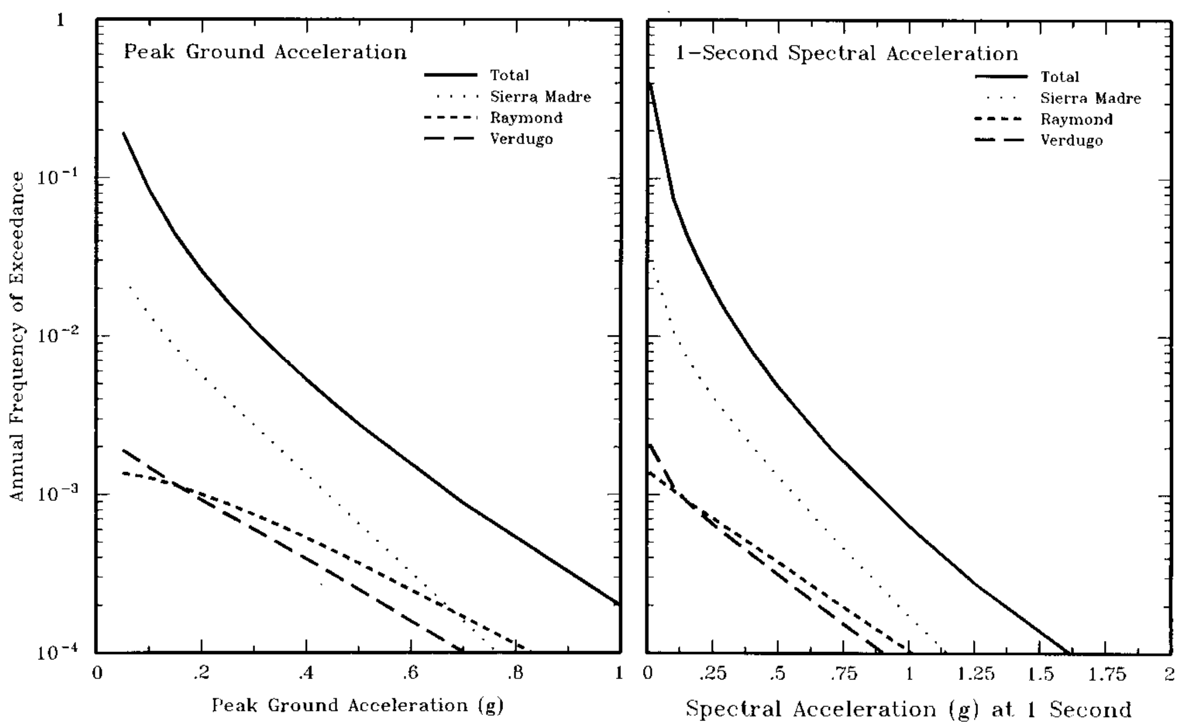


Figure 8.8. DPW Building Site Hazard Curves [Geomatrix, 1999]

Geomatrix developed site-specific spectra of Basic Safety Earthquake 1 (BSE-1) and Basic Safety Earthquake 2 (BSE-2) ground shaking, as defined by FEMA 273. The BSE-1 is the level of ground shaking that has a 10% probability of being exceeded in a 50-year period. The BSE-2 is the level of ground shaking that has a 2% probability of being exceeded in a 50-year period, but need not exceed 1.5 times the median deterministic level of ground shaking for maximum magnitude events on active faults near the site. Due to its very close proximity, Verdugo fault has potential to produce the strongest ground shaking at the site with a maximum magnitude M6.9 event (even though the Sierra Madre fault can produce a maximum magnitude M7.2 event). Site-specific response spectra of the BSE-1, the BSE-2 (probabilistic definition) and maximum magnitude events on the Verdugo and Sierra Madre faults are shown in Figure 8.9.

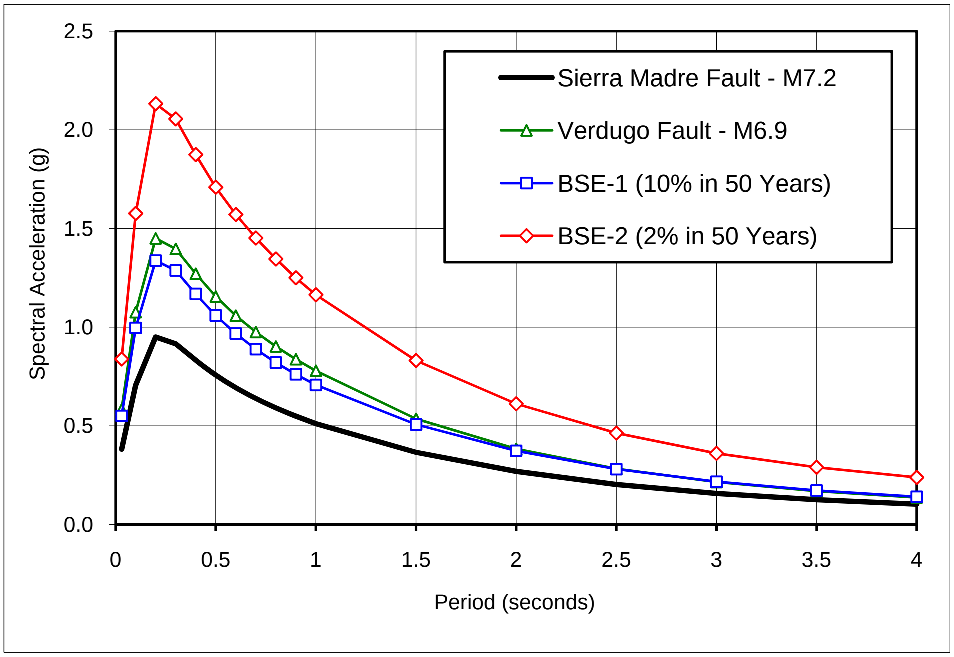


Figure 8.9. Site-Specific Response Spectra – DPW Building

8.3 *Hazus* Software - Getting Started

Before the AEBM can be used to evaluate building-specific damage and loss, the *Hazus* software must be installed and users should have some experience with the software. Chapter 2 of *Hazus-MH 2.1 User's Manual* should be referred to for help with installing and starting *Hazus*. Chapters 3 and 9 of the *Hazus-MH 2.1 User's Manual* should be referred to for running *Hazus* (with either default data or user-supplied data).

The AEBM is implemented through a variety of *Hazus* software menus and dialog boxes that begin with defining a study region, include defining ground shaking hazard and AEBM inventory, running AEBM analyses and finally viewing or printing of AEBM results. Figure 8.10 illustrates the flow of *Hazus* software elements related to the AEBM.

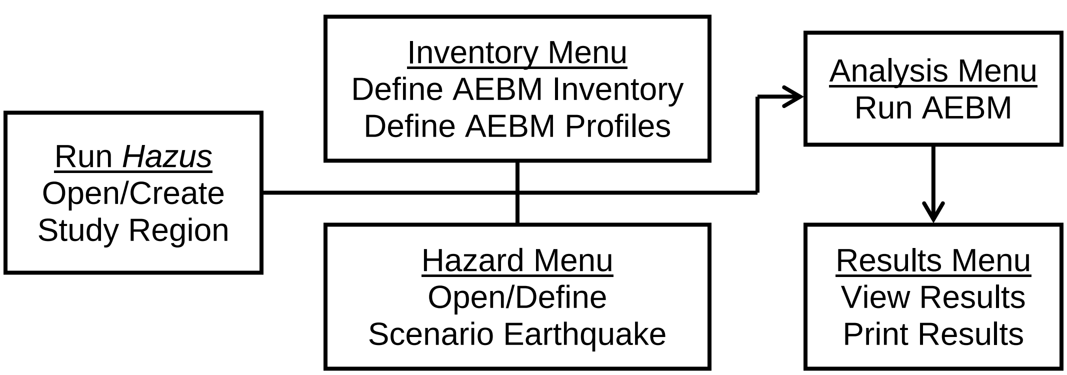


Figure 8.10. *Hazus* Software - Flowchart of AEBM Calculation of Damage and Loss

8.3.1 Defining a Study Region

As the first step, the user must define a study region that includes the location (i.e., latitude/longitude) of all buildings to be evaluated. The study region may be as small as a single census tract or as large as that used for regional loss studies. A large region provides a better picture of the spatial distribution of ground shaking (and damage and loss), but requires a greater time for *Hazus* software to aggregate inventory data that are not required for AEBM calculations. Users are cautioned that very large study regions can take hours to aggregate and run. *Hazus* requires users to define a new (or open an existing) study region when the program is initially turned on. Section 3.1 of the *Hazus-MH 2.1 User's Manual* describes the specific steps and options for creating a study region.

Los Angeles County was selected for the AEBM example to provide basis for comparing individual building losses with those for the region. Default data were used for aggregation of inventory in the study region covers over 4,000 square miles and includes a total population of more than 9,519,000 inhabitants (based on 2002 census data). There are about 2.4 million buildings in the region estimated to have a replacement value of about $690 billion, excluding contents (based on 1994 dollar value). Figure 8.11 shows a screen shot of Los Angeles County census tracts.

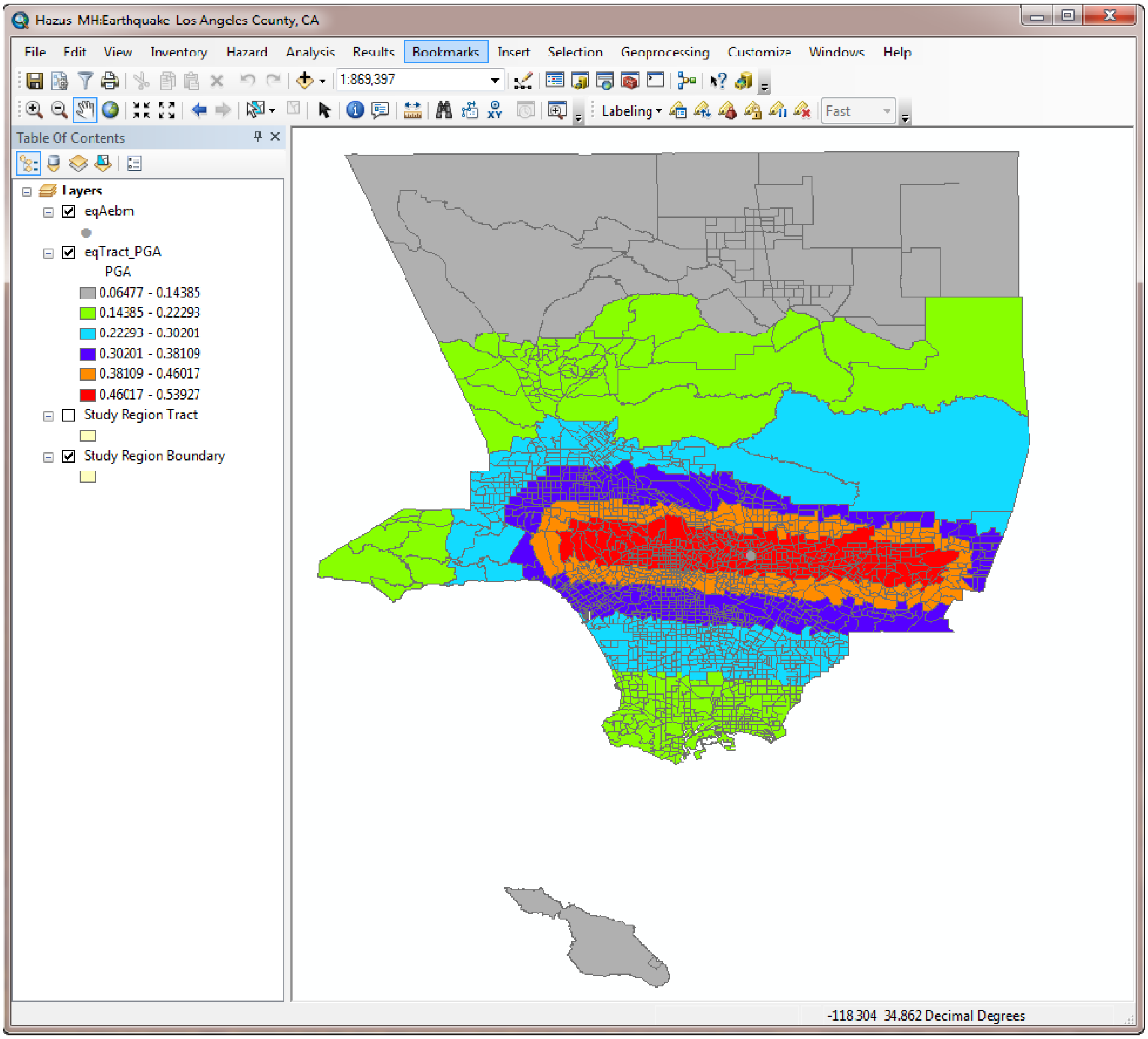


Figure 8.11. Map of Los Angeles County and Scenario Earthquake Ground Shaking

8.3.2 Defining Scenario Earthquake Ground Shaking

Users must define a scenario earthquake for calculation of ground shaking. The scenario earthquake may be a deterministic event, a probabilistic analysis of seismic hazard or by a user-supplied map of ground motion. The deterministic option will likely be the most useful and convenient method of defining AEBM ground shaking. Deterministic events may be defined based on maps of historical epicenter data, maps of seismic sources or arbitrarily defined by the user. Section 9.2 of the *Hazus-MH 2.1 User's Manual* describes these options for creating scenario earthquake ground shaking.

A magnitude M7.2 event on the Sierra Madre fault is defined as the scenario earthquake for the AEBM example. The Sierra Madre fault represents the most likely source of a major earthquake to affect the building site and an magnitude M7.2 event is the “maximum” magnitude for this fault system, as determined by a site-specific hazard study [Geomatrix, 1999]. Clearly, geotechnical expertise is crucial in determining which faults most affect ground shaking hazard at the site and what magnitude of event is possible for each fault system.

Additionally, geotechnical expertise is also essential in determining local site conditions (i.e., soil type). Based on mapped geology, available soil boring information and shear wave velocity measurements, the Geomatrix study characterized the LACDPW Headquarters building site as Site Class C (very stiff soil). Rather than importing a soil data into Hazus, the default soil type, Site Class C, was used for this example.

The *Hazus* software was used to generate scenario earthquake ground shaking for the Los Angeles study region, as shown in Figure 8.11 for 1-second spectral acceleration. Maps of scenario earthquake ground shaking are useful for AEBM calculation since it provides users with hazard data that can be compared with the results of site-specific studies. The location of the LACDPW Headquarters building is shown in Figure 8.11 (by a star) and 1-second spectral acceleration at this site is about 0.43 g. This value of spectral acceleration is about 15% less than the 0.5 g value of 1-second spectral acceleration calculated by the site-specific hazard study for a magnitude M7.2 event of the Sierra Madre fault, as shown in Figure 8.9. The difference in ground shaking calculated by *Hazus* and the site-specific study is due to different methods used for (1) soil type/amplification, (2) attenuation and (3) fault geometry/distance to site.

8.3.3 Defining AEBM Inventory Data

Users must input (or modify) a large number of “inventory” data that describe properties of individual buildings. These data are input through the **AEBM Inventory** and **AEBM Profiles** options under the **Inventory** pull-down menu. Clicking on the **AEBM Inventory** option returns a blank table with 22 data fields to be filled by the user. A right click on the mouse will display an editing menu with various options including **Add record** for manual entry of data or an **import database..** for automated entry of data. Figure 8.12 shows a portion of the Inventory table (and editing menu box) after addition of two records of the AEBM example.

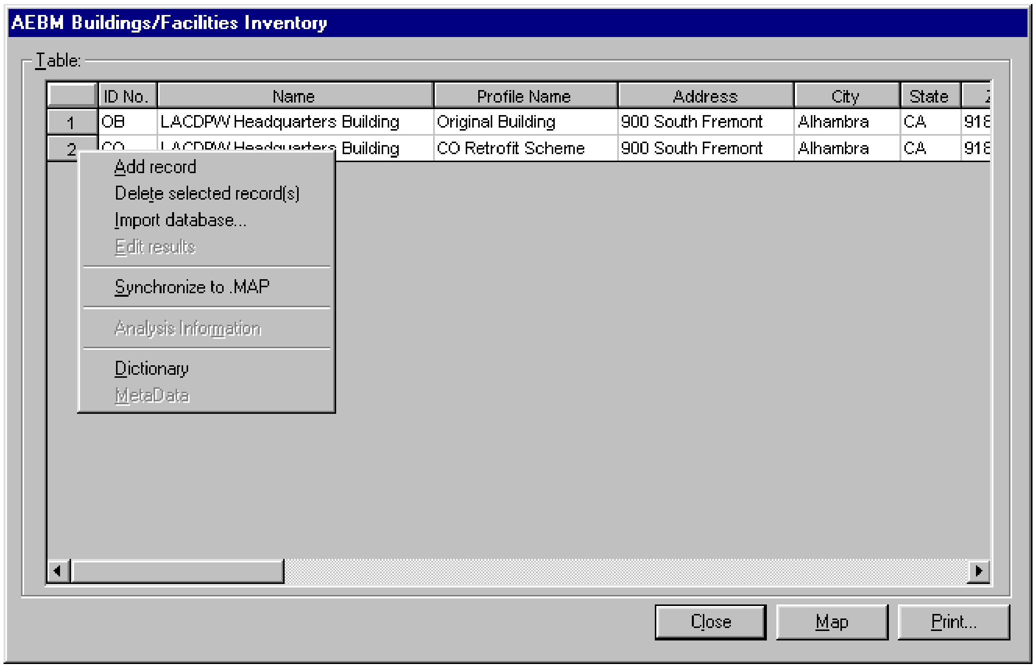


Figure 8.12. AEBM Example Inventory Table

Table 8.1 lists the 22 parameters (fields) of the Inventory table and summarizes data used for the AEBM example. In this example, there are two buildings (hence two inventory records) representing the Original Building and the CO Retrofit Scheme. Inventory data are the same for these two buildings, since the size, value, etc., of the building would not be changed as a result of the CO Retrofit Scheme. Arguably, the LACDPW Headquarters building would be of greater value after seismic retrofit, but this increase in value is not included in the AEBM example.

The source of many of the inventory data used in the AEBM example are either obvious (e.g., name and address) or are arbitrary (e.g., ID No. and Profile Name). Users must provide Latitude and Longitude data (since *Hazus* software does not automatically use address information to geo-code building location). Latitude and Longitude data may be estimated from detailed maps, GPS measurements taken at the building site or from geo-coding software contained in MapInfo or available at map-related web sites on the Internet. The latter was used to obtain the Latitude and Longitude data for the AEBM example. As shown in Figure 8.12, there is a **Map** button at the bottom of the Inventory table that may be used to show the of AEBM buildings within the study region. Mapping is a useful tool for overlaying the location of AEBM buildings with hazard contours (as shown in Figure 8.11) and also provides a “sanity check” of building location.

Building occupants, size, replacement value and operational cost data are based on or derived from information compiled by Black & Veatch during their seismic mitigation study (or in certain cases are based on generic building rates of the *Hazus-MH 2.1 Technical Manual*). These data are approximate, and in many cases just “best estimates” of actual building parameters (e.g., value of building contents). Data are rounded to one or two significant decimal places to indicate this lack of precision.

Table 8.1. Example AEBM Inventory Data

Parameter Field Name	Record No. 1	Record No.2
ID No.	OB	CO
Name	LACDPW Headquarters Building	Same as Record No. 1
Profile Name	**Original Building**	**CO Retrofit Scheme**
Address	900 South Fremont	Same as Record No. 1
City	Alhambra	Same as Record No. 1
State	CA	Same as Record No. 1
Zip Code	91803-1331	Same as Record No. 1
Latitude	34.085	Same as Record No. 1
Longitude	-118.15197	Same as Record No. 1
Daytime Occupants	1600	Same as Record No. 1
Nighttime Occupants	80	Same as Record No. 1
Building Area (sq. ft.)	400,000	Same as Record No. 1
Building Value (thous. $)	60,000	Same as Record No. 1
Contents Value (thous. $)	15,000	Same as Record No. 1
Business Inventory (thous. $)	0	Same as Record No. 1
Business Income (thous. $/day)	32	Same as Record No. 1
Wages Paid (thous. $/day)	130	Same as Record No. 1
Relocation Disruption Costs (thous. $)	280	Same as Record No. 1
Rental Costs (thous. $/day)	13	Same as Record No. 1
Ratio of Building Owner Occupied	100	Same as Record No. 1
County FIPS	06037	Same as Record No. 1
Soil type	C	C
Liquefaction Susceptibility Category	0	0
Liquefaction Susceptibility Category	0	0
WaterDepth (ft)	5	5

The number of daytime occupants (1,600) assumes a fully occupied and functional building of about 1,500 employees and 100 visitors. Nighttime occupants are assumed to be 5% of the daytime building population, since the building is not in use after hours.

The building is approximately 400,000 square feet and studies of the replacement costs of structural and nonstructural systems indicate a building value of about $60 million or about $150 per square foot. Contents value is estimated as $15 million or about $10,000 per employee. Contents includes such items as furniture, computers and telecommunication equipment.

There is no Business Inventory associated with the LACDPW Headquarters building. Business Income and Wages Paid are based on the economic rates given in Table 15.15 of the *Hazus-MH 2.1 Technical Manual* for a GOV1 occupancy. In the case of Wages Paid, the $2.18 value of wages per square foot per day given in Table 15.15 assumes 0.025 employees per square foot. The $2.18 value is factored by (1,500/400,000)/0.025 to more realistically reflect the number of employees per square foot in the LACDPW Headquarters building. Relocation Disruption and Rental Costs are based on the economic rates given in Table 15.13 of the *Hazus-MH 2.1 Technical Manual* for a GOV1 occupancy.

8.3.4 Defining Default AEBM Profile Data

The *Hazus* software uses the **Profile Name** to link each building listed in the **AEBM Inventory** table to data that define an AEBM profile of capacity, damage and loss parameters. There must be at least one AEBM profile, but the same profile can be used for more than one building listed in the **AEBM Inventory** table. In the AEBM example, the Original Building and the CO Retrofit Scheme have different profiles since they have different capacity, damage and loss parameters.

AEBM profile data is voluminous, grouped into eight sets of **AEBM Profiles** databases:

1. Building Characteristics
2. Structural Fragility Curves
3. Nonstructural Drift Fragility Curves
4. Nonstructural Acceleration Fragility Curves
5. Casualty Ratios (per occupant)
6. Building Related Repair Cost Ratios
7. Contents & Building Inventory Replacement Cost Ratios
8. Loss of Function Parameters (# of days).

As a starting point, **AEBM Profiles** databases are populated with “default” capacity, damage and loss parameters of a GBS (General Building Stock) building. The process begins with the user’s selection of the occupancy class, building type, design level and quality of construction that best represents the individual building of interest. Clicking on the **AEBM Profiles** option (of the **Inventory** pull-down menu) returns the dialog box shown in Figure 8.13.

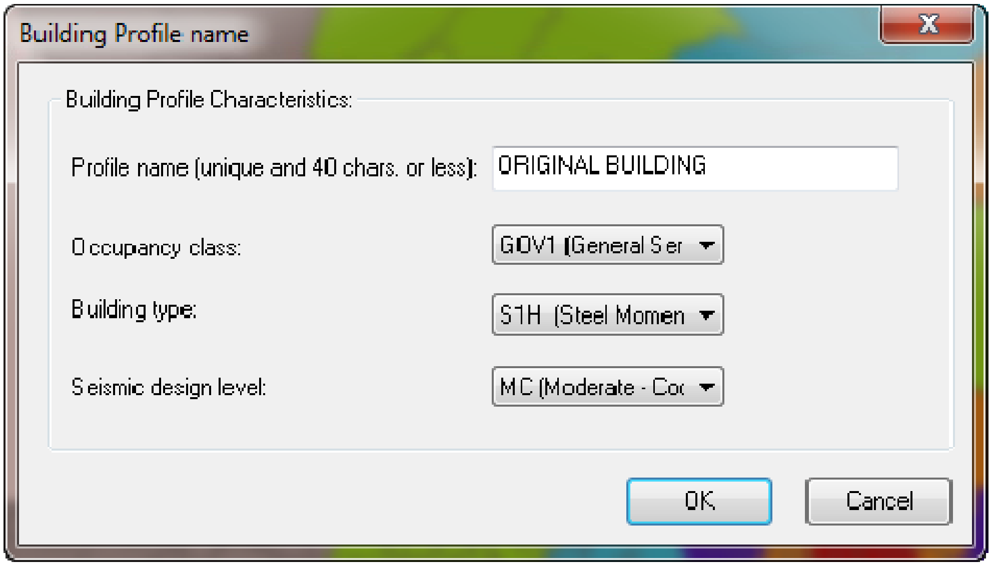


Figure 8.13. Building Profile Name Dialog Box

After the user enters the Profile Name and selects appropriate occupancy class, building type, seismic design level and building quality parameters, the *Hazus* software populates the eight **AEBM Profiles** databases with "default" data and displays the Building Characteristics table. A right click on the mouse will display an editing menu box with for adding new building profiles or editing existing profiles. Figure 8.14 shows a portion of the Building Characteristics table (and editing menu box) after addition of two records of the AEBM example

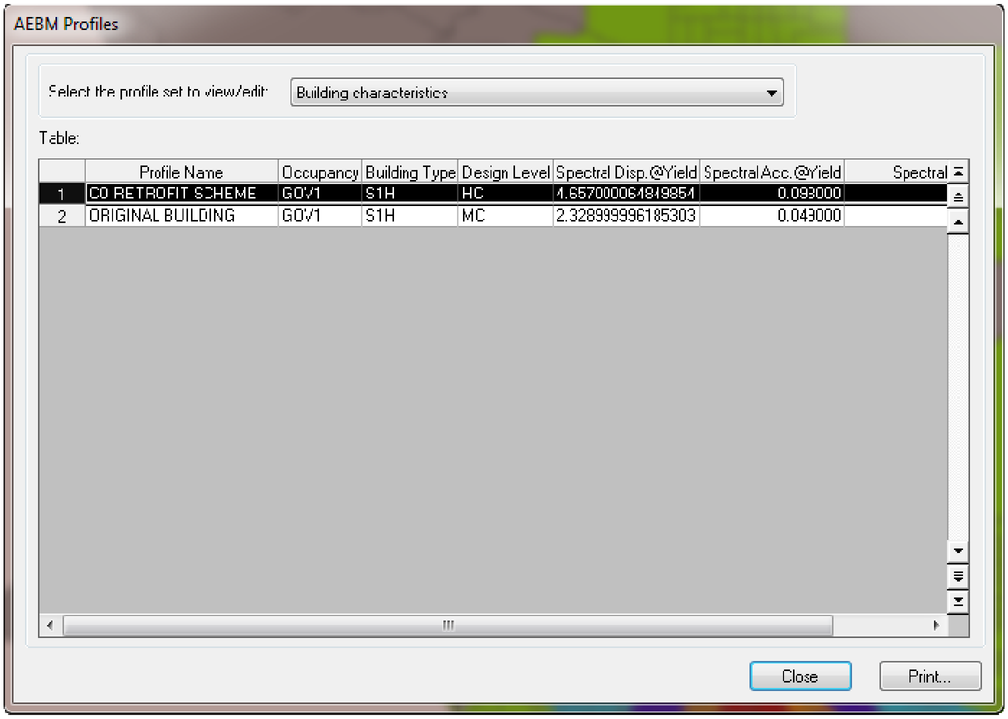


Figure 8.14. AEBM Example Building Characteristics Table

The Profile Name, Occupancy, Building Type Design Level and Building Quality (with parameters shown by blue font) cannot be edited by the user. All other "default" profile data of the Building Characteristics table and the other seven tables of **AEBM Profiles** data can be edited to better reflect actual capacity, damage and loss parameters of the buildings. Section 8.4 describes editing of these tables to include data representing the Original Building and CO Retrofit Scheme.

8.3.5 <u>Running the AEBM</u>

The AEBM may be run after the user has defined a scenario earthquake and building inventory and profile data. Clicking on the **Run** option of the **Analysis** pull-down menu returns the dialog box shown in Figure 8.15. The "Advanced Engineering Bldg Model" box should be checked before clicking on the **OK** button. The AEBM may be run without running other modules of the *Hazus* software. Scenario earthquake ground shaking will be calculated for AEBM building sites even if the **PESH** module is not checked.

8.3.6 <u>Viewing and Printing AEBM Results</u>

Results of AEBM analyses may be viewed by clicking on the **Advanced Engineering Bldg Model (AEBM)** option of the **Results** pull-down menu. A results table includes response (intersection point) data, damage state probabilities and casualty and direct economic losses for each building in the AEBM Inventory. The same data may also be viewed (and printed) in *Hazus* summary reports. Clicking on the **Other** tab of the **Summary Reports** option of the **Results** pull-down menu returns the dialog box shown in Figure 8.16.

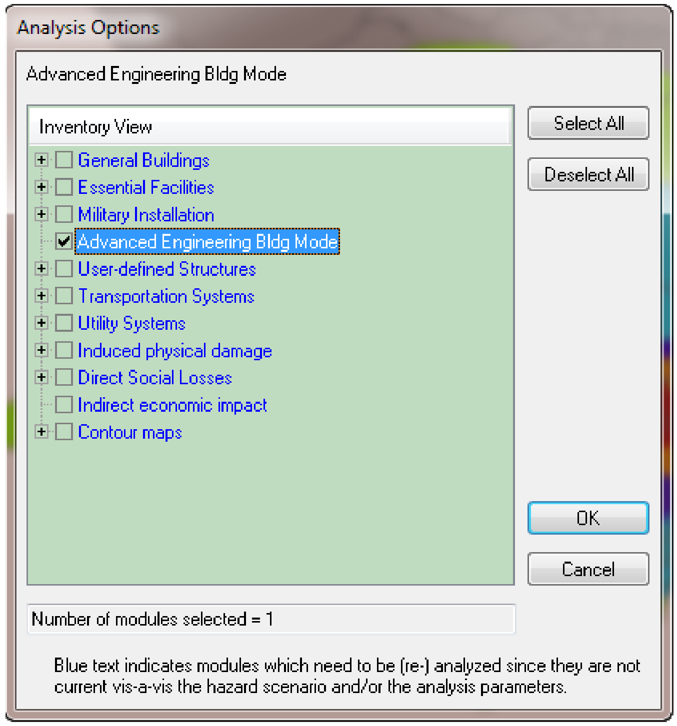


Figure 8.15. Analysis Options Dialog with AEBM Selected.

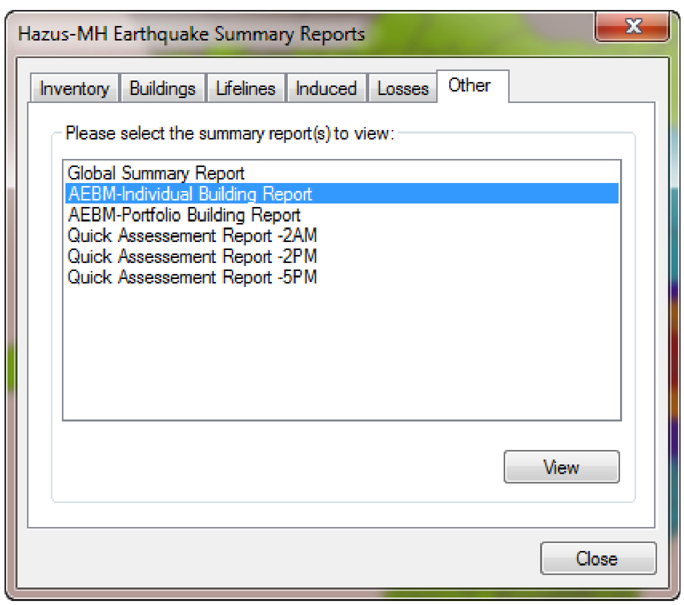
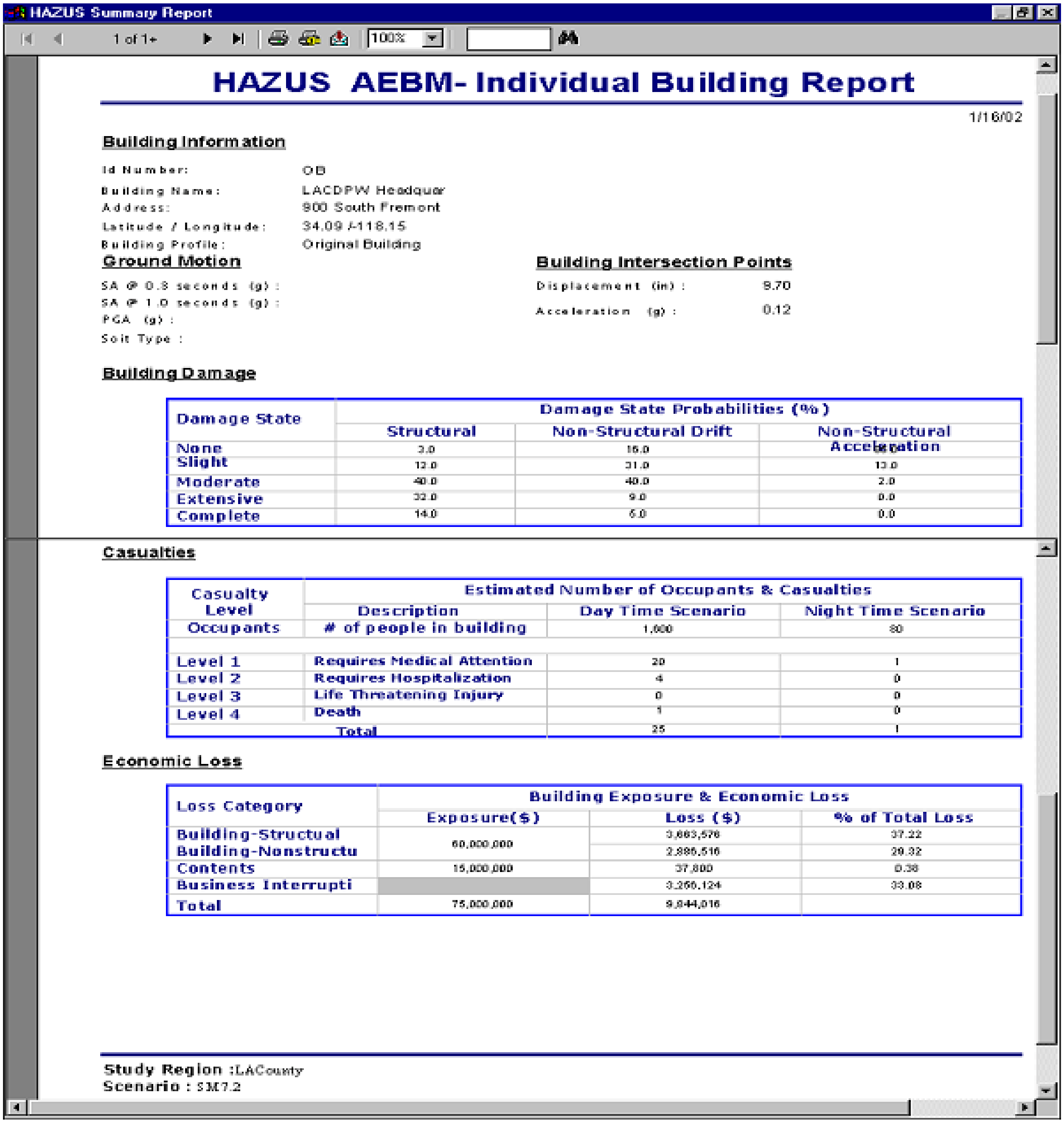


Figure 8.16. *Hazus* Summary Reports Dialog Box

Summary report options include an "AEBM – Individual Building Report" that summarizes results separately for each building in the AEBM Inventory and an "AEBM-Portfolio Building Report" which averages damage and aggregates losses for all buildings in the AEBM Inventory. Figures 8.17 and 8.18 show individual summary reports for the Original Building and the CO Retrofit Scheme (based on default AEBM profile data), respectively. These reports may be printed (by clicking on the **Printer** icon shown at the top of the window) or exported in Word, Adobe or Excel format (by clicking on the **Envelop** icon at the top of the window).



HAZUS Summary Report

1 of 1+ | 100%

HAZUS AEBM- Individual Building Report

1/16/02

Building Information

Id Number: OB
Building Name: LACDPW Headquar
Address: 900 South Fremont
Latitude / Longitude: 34.09 /-118.15
Building Profile: Original Building

Ground Motion

SA @ 0.3 seconds (g) :
SA @ 1.0 seconds (g) :
PGA (g) :
Soil Type :

Building Intersection Points

Displacement (in) : 9.70
Acceleration (g) : 0.12

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	3.0	16.0	[illegible]
Slight	12.0	31.0	13.0
Moderate	40.0	40.0	2.0
Extensive	32.0	9.0	0.0
Complete	14.0	6.0	0.0

Casualties

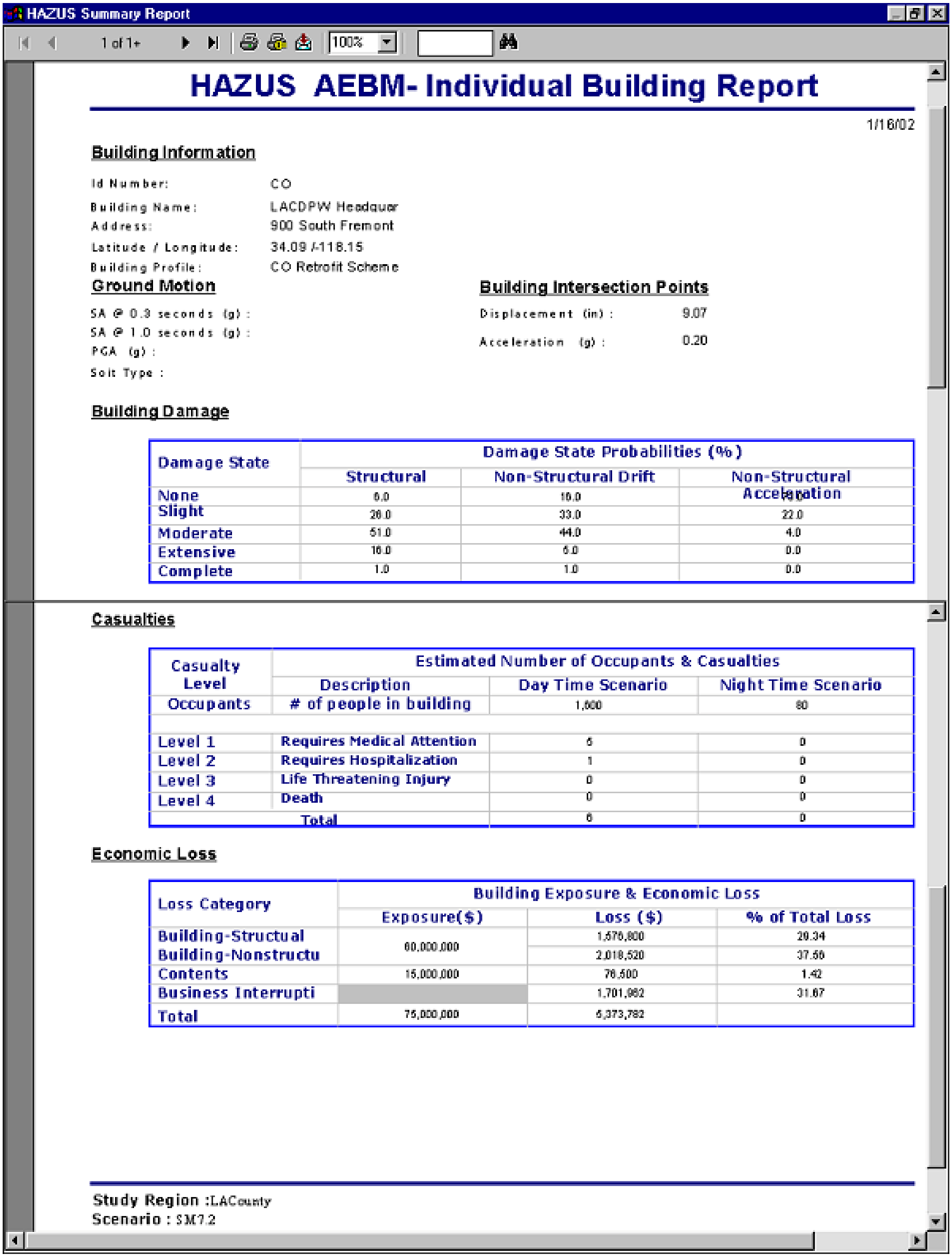
Casualty Level	Estimated Number of Occupants & Casualties		
	Description	Day Time Scenario	Night Time Scenario
Occupants	# of people in building	1,000	80
Level 1	Requires Medical Attention	20	1
Level 2	Requires Hospitalization	4	0
Level 3	Life Threatening Injury	0	0
Level 4	Death	1	0
	Total	25	1

Economic Loss

Loss Category	Building Exposure & Economic Loss		
	Exposure($)	Loss ($)	% of Total Loss
Building-Structual	60,000,000	3,683,576	37.22
Building-Nonstructu		2,886,516	29.32
Contents	15,000,000	37,800	0.38
Business Interrupti		3,266,124	33.08
Total	75,000,000	9,844,016	

Study Region :LACounty
Scenario : SM7.2

Figure 8.17. Summary Report – Original Building Results (Default AEBM Profile Data)



HAZUS Summary Report

1 of 1+ 100%

HAZUS AEBM- Individual Building Report

1/16/02

Building Information

Id Number: CO
Building Name: LACDPW Headquar
Address: 900 South Fremont
Latitude / Longitude: 34.09 /-118.15
Building Profile: CO Retrofit Scheme

Ground Motion

SA @ 0.3 seconds (g) :
SA @ 1.0 seconds (g) :
PGA (g) :
Soil Type :

Building Intersection Points

Displacement (in) : 9.07
Acceleration (g) : 0.20

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	6.0	16.0	74.0
Slight	26.0	33.0	22.0
Moderate	51.0	44.0	4.0
Extensive	16.0	6.0	0.0
Complete	1.0	1.0	0.0

Casualties

Casualty Level	Estimated Number of Occupants & Casualties		
	Description	Day Time Scenario	Night Time Scenario
Occupants	# of people in building	1,600	80
Level 1	Requires Medical Attention	6	0
Level 2	Requires Hospitalization	1	0
Level 3	Life Threatening Injury	0	0
Level 4	Death	0	0
	Total	6	0

Economic Loss

Loss Category	Building Exposure & Economic Loss		
	Exposure($)	Loss ($)	% of Total Loss
Building-Structual	60,000,000	1,576,800	29.34
Building-Nonstructu		2,018,520	37.56
Contents	15,000,000	76,500	1.42
Business Interrupti		1,701,962	31.67
Total	75,000,000	5,373,782	

Study Region :LACounty
Scenario : SM7.2

Figure 8.18. Summary Report – CO Retrofit Scheme Results (Default AEBM Profile Data)

8.4 Modifying Default AEBM Profile Data

The results shown in Figures 8.17 and 8.18 for the Original Building and the CO Retrofit Scheme, respectively, are based on default AEBM Profile data corresponding to the occupancy class, building type, seismic design level and building quality that best represent the LACDPW Headquarters building before and after seismic retrofit.

Building occupancy is GOV1, since the building provides office space for Los Angeles County Department of Public Works. The building type is S1H, since the structural system is a steel moment-resisting frame and the building is over 7 stories in height (see Table 2.1). The seismic design level of Original Building is Moderate Code since it was designed and constructed between 1941 and 1975 (see Table 2.2) and is assigned a building quality of Inferior due to the weakness of the welded connections. After strengthening of the connections, the CO Retrofit Scheme is assumed to have strength comparable to a building of High Code seismic design level and Ordinary quality.

Default AEBM Profile data are a good starting point, and can produce reasonable estimates of damage and loss (when based on the appropriate assumptions of occupancy, building type design level and quality). However, results of engineering (pushover) analyses and other building-specific data can be used to modify default data and produce more reliable estimates of damage and loss. This section illustrates modification of default data in **AEBM Profiles** databases for the Original Building and the CO Retrofit Scheme, respectively. The process begins with the user selecting the profile set (database) of interest by first clicking on the **AEBM Profiles** option of the **Inventory** pull-down menu and by then clicking on the one of the eight database sets shown in Figure 8.19.

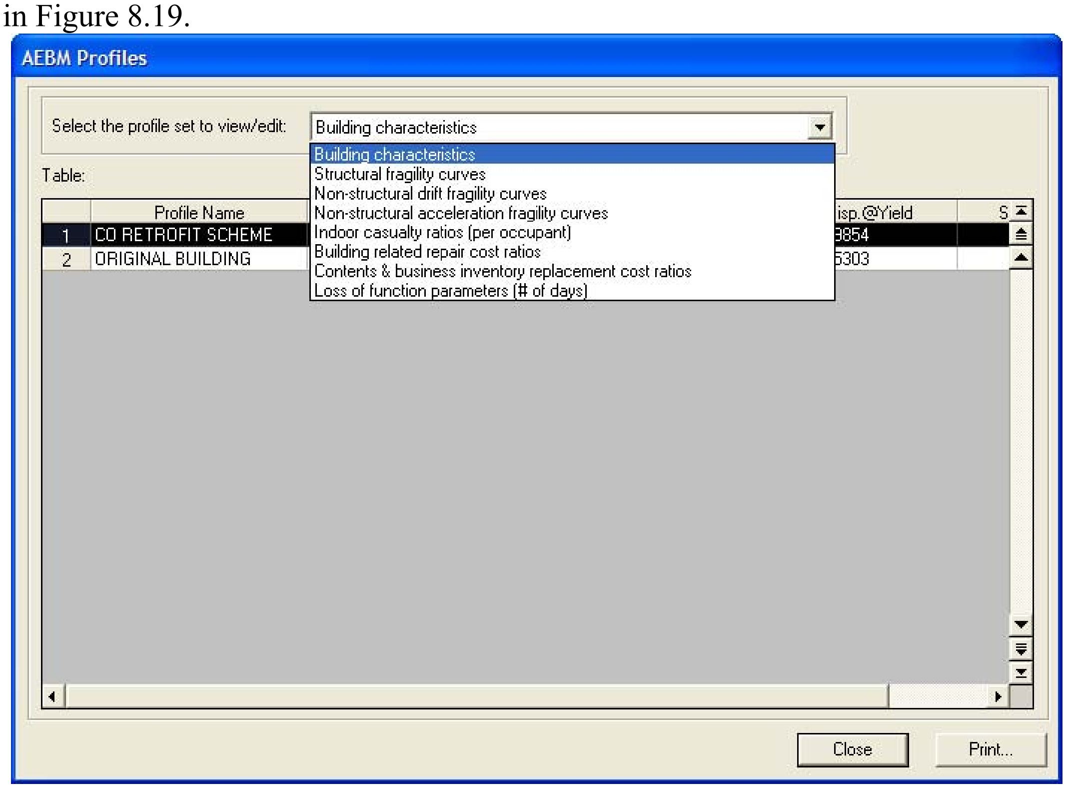


Figure 8.19. Selection of AEBM Profiles Database Set

Each profile database set is shown by a table in the *Hazus* software that has a similar format. Each table has the same number of records (e.g., two records in the AEBM example) and the first field of each table is always the Profile Name. Other fields contain various response, capacity, damage or loss parameters that are edited by directly by deleting existing (default) values and typing in new data.

The following sections describe each of the eight **AEBM Profiles** databases, listing both default and modified data and discussing the basis for modified data (e.g., results of pushover analyses).

8.4.1 Building Characteristics

Building characteristics are listed in Table 8.2 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Table 8.2. Example AEBM Profiles Data – Building Characteristics

Parameter Field Name	Record No. 1	Record No. 2
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
Occupancy	GOV1	GOV1
Building Type	S1H	S1H
Design Level	MC	MH
Spectral Disp. @ Yield	6.820	6.850
Spectral Acc. @ Yield	0.142	0.207
Spectral Disp. @ Ultimate	17.150	22.690
Spectral Acc. @ Ultimate	0.195	0.331
Duration Factor: Small EQ	0.50	0.90
Duration Factor: Moderate EQ	0.30	0.70
Duration Factor: Large EQ	0.10	0.50
Elastic Damping (%)	*5*	*5*
Ratio of Contents: Ground Level	*0.20*	*0.20*

Modified capacity curve parameters (i.e., spectral displacement acceleration corresponding to the yield and ultimate points) are based on the pushover curves of the Original Building and the CO Retrofit Scheme, shown in Figures 8.6 and 8.7, respectively. In the case of the Original Building, capacity curve properties are based on pushover strength consistent with UCSD test data. The pushover curves (plots of base shear versus roof displacement) were generated by SAP 2000 Nonlinear analyses of the structural systems. Capacity curves (plots of spectral acceleration versus spectral displacement) corresponding to these pushover curves were also generated by the SAP 2000 analyses, using the conversion methods described in Section 5.2.1. Yield and ultimate "control" points are based on *Hazus* compatible versions of these capacity curves in accordance with Section 5.2.2. *Hazus* compatible capacity curves and their control points of the Original Building and the CO Retrofit Scheme are shown in Figure 8.20 with the respective capacity curves based on pushover results.

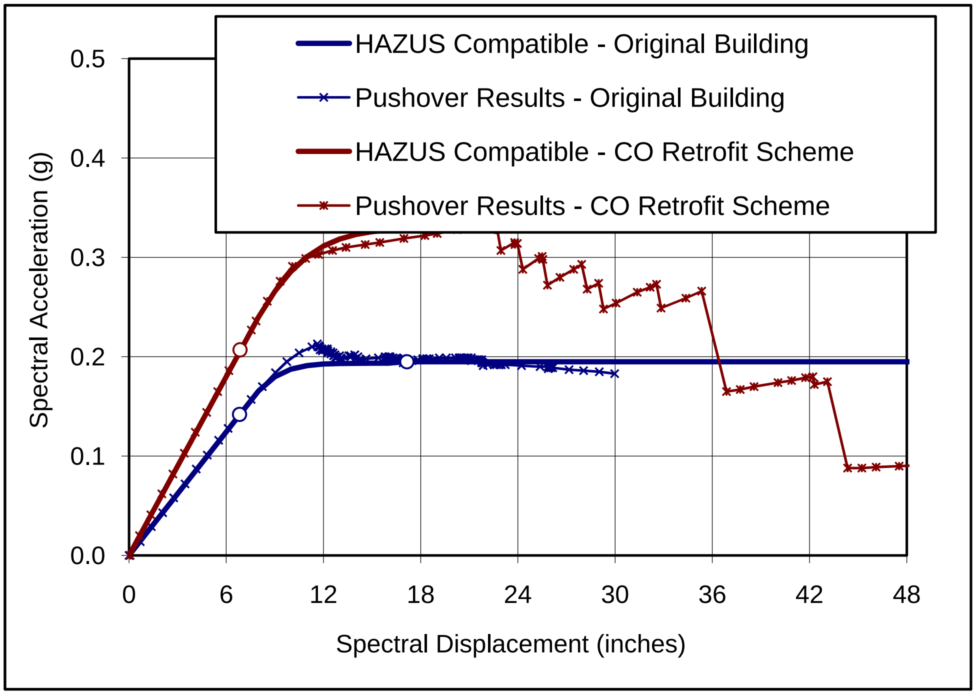


Figure 8.20. Original Building and CO Retrofit Scheme Capacity Curves

Default values of the duration factors are modified (slightly) to be consistent with the recommendations of Table 5.2. Default values of the elastic damping term and contents ratio are considered appropriate and are not modified. Note, in Table 8.2 and subsequent tables summarizing **AEBM Profiles** data, *italics* denote that default data are used without modification.

8.4.2 <u>Structural Fragility Curves</u>

Structural fragility curve parameters (medians and betas) are listed in Table 8.3 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Modified values of structural damage-state medians are based on combination of recommendations of Appendix B of FEMA 351 [FEMA, 2000] and the pattern of damage predicted by the results of the pushover analyses. For the Original Building, damage states are based primarily on the extent of damage to welded connections as predicted by the pushover over analysis. Figure 8.6 includes a plot showing the number of damaged connections as a function of roof displacement. Based on the recommendations of Table B-4 of FEMA 351, Slight damage corresponds to 2% of welded connections with damage and Figure 8.6 indicates that this fraction of damaged weld occurs at about 10 inches of roof displacement. Using the same approach, Moderate damage occurs at about 13 inches, Extensive damage at about 18 inches and Complete damage at about 30 inches. Factoring these roof displacements by α_2 = 0.74, as per Equation (6-1), the corresponding spectral displacements are Slight damage = 7.4 inches, Moderate damage = 9.6 inches, Extensive damage = 13.3 inches and Complete damage = 22.2 inches.

Table 8.3. Example AEBM Profiles Data – Structural Fragility Curves

Parameter Field Name	**Record No. 1**	**Record No. 2**
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
Slight/Median	7.60	11.10
Slight/Beta	0.75	0.65
Moderate/Median	9.70	15.10
Moderate/Beta	0.80	0.65
Extensive/Median	15.40	30.00
Extensive/Beta	0.85	0.65
Complete/Median	24.20	42.50
Complete/Beta	0.95	0.70

The CO Retrofit Scheme does not fail connections. Rather, the pushover curve indicates first yielding of elements and subsequent failure, leading to a loss of global strength. Referring to the CO Retrofit Scheme capacity curve in Figure 8.20, it may be seen that yielding does not occur until after about 10 inches of spectral displacement and that significant yielding but no loss of strength corresponds to about 15 inches of spectral displacement. At about 30 inches, some elements begin to fail and at about 42 inches more than one-half of the elements have failed. These spectral displacements represent reasonable values of Sight, Moderate, Extensive and Complete damage-state medians (that define the thresholds of damage states).

The modified damage-state medians of Table 8.3, although similar in value to those of the above discussion, are based on Equation (B-13) of FEMA 351 and assumptions of damage state inter-story drift ratios of Table 8.4. Equation (B-13) is similar to Equation (6-1) with the addition of two additional terms, α_3 and $\alpha_{4,ds}$, which adjust damage-state for higher-mode effects and non-uniform mode shape, respectively:

$$\hat{S}_{d,ds} = \frac{\alpha_2 \Delta_{ds} H_R}{\alpha_3 \alpha_{4,ds}} \qquad \text{(B-13, FEMA 351)}$$

The α_3 and $\alpha_{4,ds}$, factors are described in FEMA 351, including formulas for these factors that that are based on height (number of stories) of the building. Tables 8.4 and 8.5 summarize pertinent factors and illustrate calculation of structural damage-state medians for the Original Building and CO Retrofit Scheme, respectively.

Table 8.4. Calculation of Structural Damage State Medians – Original Building

Parameter	Structural Damage State			
	Slight	Moderate	Extensive	Complete
Drift ratio - Δ_{ds}	0.01	0.0125	0.0175	0.025
Building height (inches)	1,848			
Pushover modal factor, α_2 – Equation (5-2)	0.73			
Spectral Displacement (inches) – Equation (6-1)	13.6	17.0	23.8	34.0
Higher-mode factor, α_3 – Eq. (B-14) FEMA 351	1.4			
Mode-shape factor, $\alpha_{4,ds}$ – Eq. (B-15) FEMA 351	1.27	1.25	1.1	1.0
Median spectral displacement of damage state, ds, $S_{d,ds}$ – Eq. (B13) of FEMA 351 (inches)	7.6	9.7	15.4	24.2
Median spectral displacement of damage state based on results of pushover analyses	7.4	9.6	13.3	22.2

Table 8.5. Calculation of Structural Damage State Medians – CO Retrofit Scheme

Parameter	Structural Damage State			
	Slight	Moderate	Extensive	Complete
Drift ratio - Δ_{ds}	0.015	0.020	0.035	0.045
Building height (inches)	1,848			
Pushover modal factor, α_2 – Equation (5-2)	0.74			
Spectral Displacement (inches) – Equation (6-1)	19.8	26.4	46.2	59.2
Higher-mode factor, α_3 – Eq. (B-14) FEMA 351	1.4			
Mode-shape factor, $\alpha_{4,ds}$ – Eq. (B-15) FEMA 351	1.27	1.25	1.1	1.0
Median spectral displacement of damage state, ds, $S_{d,ds}$ – Eq. (B13) of FEMA 351 (inches)	11.1	15.1	30.0	42.5
Median spectral displacement of damage state based on results of pushover analyses	10	15	30	42

Figure 8.21 illustrates the location of structural damage-state median points on the capacity curves of the Original Building and the CO Retrofit Scheme, respectively.

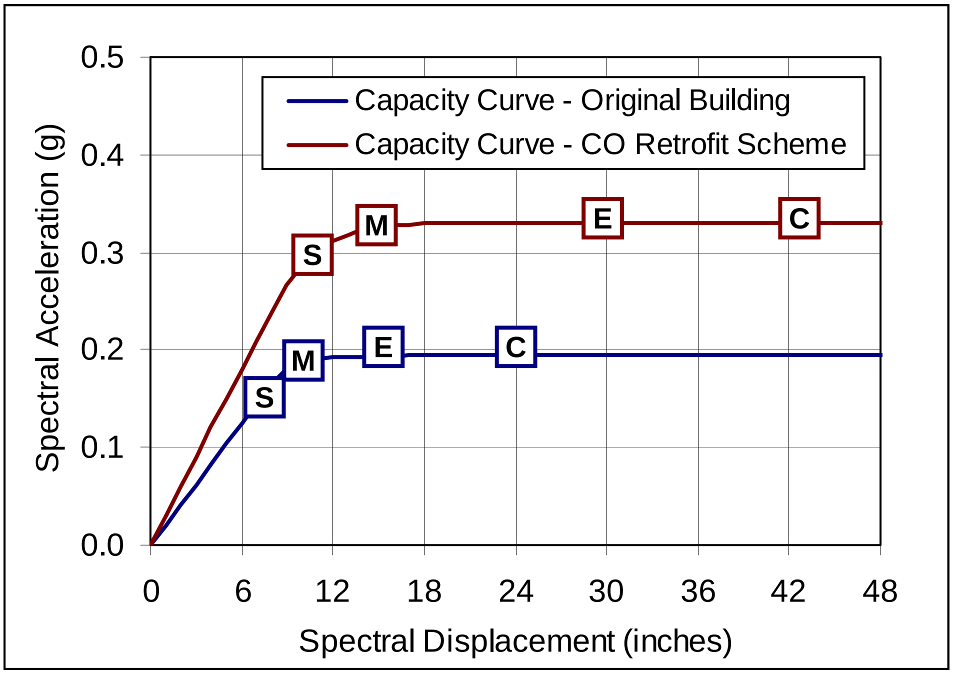


Figure 8.21. Structural Fragility – Damage-State Medians

Modified values of the structural damage-state betas medians are based on Table 6.7. The Original Building is assumed to have "moderate" to "large" capacity and damage variability due to uncertainty in the performance of connections. Interpolating between values, Table 6.7 suggests a beta of 0.75 for minor degradation ($\kappa \geq 0.9$), 0.85 for major degradation ($\kappa = 0.5$) and to about 1.0 for extreme degradation ($k \leq 0.1$).

Extreme degradation is not expected since $\kappa = 0.30$ for the duration of shaking associated with the scenario earthquake. Shaking duration applies to post-yield response and therefore applies primarily to Extensive and Complete damage states with little or minimal affect on Slight and Moderate damage states. The beta value of 0.75 selected for Slight damage assumes no degradation at this level of response. The beta values of other damage states increase progressively, Moderate damage – 0.80, Extensive damage - 0.85 and Complete damage – 0.95. A beta value of 0.95 for Complete damage reflects degradation between major and extreme ($\kappa = 0.3$).

The CO Retrofit Scheme is assumed to have "small" to "moderate" capacity and damage variability due to a reduction in uncertainty associated with the repair of welded connections. Further, repair of connections reduces the amount of degradation of the structural system that is expected to occur. Interpolating between values, Table 6.7 suggests a beta of 0.65 for minor degradation that is used for Slight through Extensive damage states, with a small increase to a beta of 0.70 for Complete damage.

8.4.3 Nonstructural Drift Fragility Curves

Nonstructural drift fragility parameters (medians and betas) are listed in Table 8.6 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Table 8.6. Example AEBM Profiles Data – Nonstructural Drift Fragility Curves

Parameter Field Name	Record No. 1	Record No. 2
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
Slight/Median	5.70	5.60
Slight/Beta	0.80	0.65
Moderate/Median	9.70	9.40
Moderate/Beta	0.85	0.65
Extensive/Median	22.00	21.50
Extensive/Beta	0.90	0.65
Complete/Median	48.40	47.20
Complete/Beta	1.00	0.75

Modified values of nonstructural drift damage-state medians are based on Equation (6-2) assuming drift to be essentially uniform over the height of the building (i.e., $F_{\phi P,ds} = 1.0$). Values of building height, H_R, and modal factor, α_2, are the same as those given in Table 8.4 and 8.5. Note, median values are slightly different for the Original Building and the CO Retrofit Scheme due a slight difference in the modal factor, α_2.

Modified values of nonstructural drift damage-state betas are based on Table 6.7 following the same approach and assumptions used to select structural damage-state betas (see discussion in the previous section).

8.4.4 Nonstructural Acceleration Fragility Curves

Nonstructural acceleration fragility parameters (medians and betas) are listed in Table 8.7 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Default values nonstructural damage-state medians (based on Moderate code design) are used for both the Original Building and the CO Retrofit Scheme on the basis that seismic upgrade of acceleration-sensitive components (e.g., seismic anchorage and bracing of equipment) is not part of the CO Retrofit Scheme. Modified values of nonstructural damage-state betas are based on Table 6.7 assuming a large variability (i.e., uncertainty) in damage variability of these components (since they are not being seismically upgraded).

Table 8.7. Example AEBM Profiles Data – Nonstructural Acceleration Fragility Curves

Parameter Field Name	Record No. 1	Record No. 2
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
Slight/Median	*0.25*	0.25
Slight/Beta	0.65	0.65
Moderate/Median	*0.50*	0.50
Moderate/Beta	0.65	0.65
Extensive/Median	*1.00*	1.00
Extensive/Beta	0.65	0.65
Complete/Median	*2.00*	2.00
Complete/Beta	0.65	0.65

8.4.5 Casualty Ratios (Per Occupant)

Casualty ratio (per occupant) parameters are listed in Table 8.8 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Default casualty rates are used for both the Original Building and the CO Retrofit Scheme. Only the parameter that defines the ratio of building area collapsed is modified using Equation (7-1) based on failure mode probabilities that distinguish between the collapse potential of the Original Building and that of the CO Retrofit Scheme.

Based on engineering evaluations (and judgement) and reflecting a high degree of uncertainty, the Original Building is assumed to be equally likely of having no collapse, partial collapse of a single story or global collapse of the entire structure, given that it has reached a state of Complete structural damage. Partial collapse would affect about 1/10 of total building area. Using Equation (7-1), the Collapse Factor is calculated:

$$\mathbf{P}\left[\mathbf{COL}\,|\,\mathbf{STR_5}\right] = 0.33\times0.0 + 0.33\times0.1 + 0.33\times1.0 = 36\% \qquad (8\text{-}1)$$

With strengthening of connections, the CO Retrofit Scheme is assumed to be much less likely of global collapse (i.e. only a 10% probability), but still likely to have some form of collapse (i.e., 50% probability), given that it has reached a state of Complete structural damage. Again using Equation (7-1), the Collapse Factor is calculated:

$$\mathbf{P}\left[\mathbf{COL}\,|\,\mathbf{STR_5}\right] = 0.50\times0.0 + 0.40\times0.1 + 0.10\times1.0 = 14\% \qquad (8\text{-}2)$$

Table 8.8. Example AEBM Profiles Data – Casualty Ratios (per Occupant)

Parameter Field Name	Record No. 1		Record No. 2	
	Default	**Modified**	**Default**	**Modified**
Name	Original Building		CO Retrofit Scheme	
Slight/Level 1	0.00050	*0.00050*	0.00050	*0.00050*
Slight/Level 2	0.00000	*0.00000*	0.00000	*0.00000*
Slight/Level 2	0.00000	*0.00000*	0.00000	*0.00000*
Slight/Level 2	0.00000	*0.00000*	0.00000	*0.00000*
Moderate/Level 1	0.00200	*0.00200*	0.00200	*0.00200*
Moderate/Level 2	0.00025	*0.00025*	0.00025	*0.00025*
Moderate/Level 3	0.00000	*0.00000*	0.00000	*0.00000*
Moderate/Level 4	0.00000	*0.00000*	0.00000	*0.00000*
Extensive/Level 1	0.01000	*0.01000*	0.01000	*0.01000*
Extensive/Level 2	0.00100	*0.00100*	0.00100	*0.00100*
Extensive/Level 3	0.00001	*0.00001*	0.00001	*0.00001*
Extensive/Level 4	0.00001	*0.00001*	0.00001	*0.00001*
Complete/Level 1	0.05000	*0.05000*	0.05000	*0.05000*
Complete/Level 2	0.01000	*0.01000*	0.01000	*0.01000*
Complete/Level 3	0.00010	*0.00010*	0.00010	*0.00010*
Complete/Level 4	0.00010	*0.00010*	0.00010	*0.00010*
Complete w/Collapse/Level 1	0.40000	*0.40000*	0.40000	*0.40000*
Complete w/Collapse/Level 2	0.20000	*0.20000*	0.20000	*0.20000*
Complete w/Collapse/Level 3	0.05000	*0.05000*	0.05000	*0.05000*
Complete w/Collapse/Level 4	0.10000	*0.10000*	0.10000	*0.10000*
Ratio of Building Area Collapsed	0.03	0.36	0.03	0.14

8.4.6 Building Related Repair Cost Ratios

Building related repair cost ratio parameters are listed in Table 8.9 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Modified structure (STR) repair cost ratios are based on Table B-9 of FEMA 351. "Pre-Northridge" ratios are used for the Original Building and "Post-Northridge" ratios are used for the CO Retrofit Scheme. Cost ratios are adjusted to reflect that about one-half of the value of the structural system (i.e., \$12 million = 1/2 x 0.40 x \$60 million) of the LACDPW Headquarters building is associated with basement and foundation structures that are not susceptible to ground shaking damage. For the Original Building, the repair cost ratios for Slight, Moderate and Extensive damage states are 0.04, 0.10 and 0.40, respectively, based on one-half of the "Pre-Northridge" ratios given in Table B-9 of FEMA 351. "Pre-Northridge" repair cost ratios of FEMA 351 reflect actual costs of repair to buildings damaged during the 1994 Northridge earthquake, including costs of post-earthquake inspection of connections. The repair cost of Complete damage is 100% assuming that basement and foundation structures could not be salvaged if the building was a total loss.

Table 8.9. Example AEBM Profiles Data – Building Related Repair Cost Ratios

Parameter Field Name	**Record No. 1**	**Record No. 2**
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
STR/Slight	0.04	0.00
STR/Moderate	0.10	0.05
STR/Extensive	0.40	0.25
STR/Complete	1.00	1.00
NSD/Slight	*0.02*	*0.02*
NSD/Moderate	*0.10*	*0.10*
NSD/Extensive	*0.50*	*0.50*
NSD/Complete	*1.00*	*1.00*
NSA/Slight	*0.02*	*0.02*
NSA/Moderate	*0.10*	*0.10*
NSA/Extensive	*0.50*	*0.50*
NSA/Complete	*1.00*	*1.00*
Ratio: STR to Building Value	0.40	0.40
Ratio: NSD to Building Value	0.20	0.20

Default repair cost ratios are used for both nonstructural drift-sensitive (NSD) and nonstructural acceleration-sensitive (NSA) systems.

Modified ratios of structural system value and nonstructural drift-sensitive system value to total building value are based on estimates of the actual costs of these systems developed during the engineering evaluation of seismic upgrade options. The modified ratios reflect an approximate \$24 million replacement value of the structural system, one-half of which is associated with basement and foundation structures, as mentioned above. Nonstructural drift-sensitive systems have a replacement value of about \$12 million and nonstructural acceleration-sensitive systems have a replacement value of about \$24 million. These system replacement costs sum to the total building replacement cost of \$60 million.

8.4.7 Contents & Building Inventory Replacement Cost Ratios

Contents and inventory replacement cost ratio parameters are listed in Table 8.10 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively. Default values of these parameters are used in all cases.

Table 8.10. Example AEBM Profiles Data – Contents/Inventory Replacement Cost Ratios

Parameter Field Name	Record No. 1	Record No. 2
	Modified	**Modified**
Name	Original Building	CO Retrofit Scheme
Contents/Slight	*0.01*	*0.01*
Contents/Moderate	*0.05*	*0.05*
Contents/Extensive	*0.25*	*0.25*
Contents/Complete	*0.50*	*0.50*
Inventory/Slight	*0.00*	*0.00*
Inventory/Moderate	*0.00*	*0.00*
Inventory/Extensive	*0.00*	*0.00*
Inventory/Complete	*0.00*	*0.00*

8.4.8 Loss of Function Parameters

Loss of function parameters are listed in Table 8.11 with values of default and modified data for the Original Building and the CO Retrofit Scheme, respectively.

Modified values of the time to restore loss of function are based on the mean repair time values and loss-of-function multipliers given in Table B-10 of FEMA 351 for 9-story WSMF buildings, limited to a maximum of 30 days. "Pre-Northridge" values are used for the Original Building and "Post-Northridge" values are used for the CO Retrofit Scheme. The values given in Table B-10 acknowledge differences in repair time based on building height (i.e., building size). However, these values represent commercial building occupancy and do not recognize that government services are expected to be restored in a relatively short period of time (even if the building is closed). Thus, the maximum time to restore loss of function is set at 30 days.

Modified values of the time to make all repairs and full recovery are based on the mean repair time values given in Table B-10 of FEMA 351 for 9-story WSMF buildings, factored by recovery time multipliers. "Pre-Northridge" values are used for the Original Building and "Post-Northridge" values are used for the CO Retrofit Scheme. Recovery time multipliers are 1.0 for Slight damage, 3.0 for Moderate and Extensive damage states, and 2.0 for Complete damage, consistent with the ratios of recovery times to repair times given in Tables 15.11 and 15.10, respectively, of the *Hazus-MH 2.1 Technical Manual* for government (GOV1) buildings.

Table 8.11. Example AEBM Profiles Data – Loss of Function Parameters

Parameter Field Name	Record No. 1 Modified	Record No. 2 Modified
Name	Original Building	CO Retrofit Scheme
Function Loss/None (Days)	0	0
Function Loss/Slight (Days)	0	0
Function Loss/Moderate (Days)	5	4
Function Loss/Extensive (Days)	30	30
Function Loss/Complete (Days)	30	30
Recovery Time/None (Days)	0	0
Recovery Time/Slight (Days)	0	0
Recovery Time/Moderate (Days)	150	120
Recovery Time/Extensive (Days)	540	540
Recovery Time/Complete (Days)	720	720
Recapture Factor/Business Income	*0.80*	*0.80*
Recapture Factor/Wages	*0.80*	*0.80*

Default recapture factors are used for both business income and wages.

8.5 Example AEBM Results

After the modification of default **AEBM Profiles** data, the AEBM may be run, as described in Section 8.3.5 and the results viewed and printed, as described in Section 8.3.6.

Figures 8.22 and 8.23 show individual summary reports for the Original Building and the CO Retrofit Scheme, respectively. These reports are the same as those shown Figures 8.17 and 8.18, respectively, except that results are now based on modified AEBM profile data and represent the most reliable estimates of damage and losses for LACDPW Headquarters building due to scenario earthquake ground shaking. Summary results indicate that the CO Retrofit Scheme would substantially reduce structural damage (and associated structural losses by more than a factor of 15), virtually eliminate serious injuries and deaths, and reduce total direct economic loss by about a factor of 5 for scenario earthquake ground shaking (e.g., a magnitude M7.2 event on the Sierra Madre fault).

A note of caution to users, ground motion (spectral acceleration) values may not be accurately reported in individual building reports. Users can verify suspicious values of spectral acceleration (e.g., the 1-second spectral acceleration of 0.07 g shown in Figures 8.22 and 8.23 seems low) with ground motion results of *Hazus* for the census tract(s) where buildings are located. In this example, the LACDPW Headquarters building is located in Census Tract 06037480802 and *Hazus* shows a 1-second spectral acceleration of 0.43 g for this census tract.

Figure 8.22. Summary Report – Original Building Results

HAZUS Summary Report

1 of 1+ 100%

HAZUS AEBM- Individual Building Report

1/19/02

Building Information

Id Number:	OB
Building Name:	LACDPW Headquar
Address:	900 South Fremont
Latitude / Longitude:	34.09 /-118.15
Building Profile:	Original Building

Ground Motion

SA @ 0.3 seconds (g):	0.12
SA @ 1.0 seconds (g):	0.07
PGA (g):	0.33
Soil Type:	Very thick soft/medium stiff clays

Building Intersection Points

Displacement (in):	9.26
Acceleration (g):	0.20

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	40.0	27.0	64.0
Slight	13.0	25.0	28.0
Moderate	20.0	31.0	7.0
Extensive	12.0	12.0	1.0
Complete	16.0	5.0	0.0

Casualties

Casualty Level	Estimated Number of Occupants & Casualties		
	Description	Day Time Scenario	Night Time Scenario
Occupants	# of people in building	1,600	80
Level 1	Requires Medical Attention	47	2
Level 2	Requires Hospitalization	20	1
Level 3	Life Threatening Injury	5	0
Level 4	Death	9	1
	Total	80	4

Economic Loss

Loss Category	Building Exposure & Economic Loss		
	Exposure($)	Loss ($)	% of Total Loss
Building-Structual	60,000,000	5,493,120	50.64
Building-Nonstructu		2,112,720	19.48
Contents	15,000,000	118,350	1.09
Business Interrupti		3,123,024	28.79
Total	75,000,000	10,847,214	

Study Region : LACounty
Scenario : SM7.2

Figure 8.23. Summary Report – CO Retrofit Scheme Results

HAZUS Summary Report

1 of 1+ 100%

HAZUS AEBM- Individual Building Report

1/19/02

Building Information

Id Number:	CO
Building Name:	LACDPW Headquar
Address:	900 South Fremont
Latitude / Longitude:	34.09 /-118.15
Building Profile:	CO Retrofit Scheme

Ground Motion

SA @ 0.3 seconds (g) :	0.12
SA @ 1.0 seconds (g) :	0.07
PGA (g) :	0.33
Soil Type :	Very thick soft/medium stiff clays

Building Intersection Points

Displacement (in) :	7.20
Acceleration (g) :	0.25

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	75.0	35.0	[illegible]
Slight	13.0	31.0	36.0
Moderate	11.0	30.0	13.0
Extensive	1.0	4.0	2.0
Complete	1.0	1.0	0.0

Casualties

Casualty Level	Estimated Number of Occupants & Casualties		
	Description	Day Time Scenario	Night Time Scenario
Occupants	# of people in building	1,600	80
Level 1	Requires Medical Attention	2	0
Level 2	Requires Hospitalization	0	0
Level 3	Life Threatening Injury	0	0
Level 4	Death	0	0
	Total	2	0

Economic Loss

Loss Category	Building Exposure & Economic Loss		
	Exposure($)	Loss ($)	% of Total Loss
Building-Structual	60,000,000	327,600	14.04
Building-Nonstructu		1,435,440	61.54
Contents	15,000,000	217,200	9.31
Business Interrupti		352,413	15.11
Total	75,000,000	2,332,653	

Study Region : LACounty
Scenario : SM7.2

8.5.1 Interpretation

Individual building results from AEBM analyses may be evaluated (and better understood) by comparison with the results of regional studies for the same scenario earthquake. Table 8.12 provides such a comparison of AEBM example results with building-related losses of the Los Angeles County study region due to a magnitude M7.2 earthquake on the Sierra Madre fault.

Table 8.12. Comparison of AEBM Example and Los Angeles County Study Region Losses for a Magnitude M7.2 Earthquake on the Sierra Madre Fault

Parameter	Exposure	Loss	Ratio
AEBM Example Results - Original Building			
Direct Economic Loss – Structural System	$24 million	$5.49 million	22.9%
Direct Economic Loss – Total Building	$60 million	$7.72 million	12.9%
Direct Economic Loss – Business Interruption	1 x bldg. value	$3.12 million	5.2%
Daytime Casualties - All	1,600	80	50/1,000
Daytime Casualties – Immediate Deaths	1,600	9	6/1,000
AEBM Example Results – CO Retrofit Scheme			
Direct Economic Loss – Structural System	$24 million	$0.33 million	1.4%
Direct Economic Loss – Total Building	$60 million	$1.98 million	3.3%
Direct Economic Loss – Business Interruption	1 x bldg. value	$0.35 million	0.6%
Daytime Casualties - All	1,600	2	1.3/1,000
Daytime Casualties – Immediate Deaths	1,600	0	0.2/1,000
Los Angeles County Study Region – Default Inventory			
Direct Economic Loss – Structural System	0.25 x bldg. value	$4.09 billion	3.5%
Direct Economic Loss – Total Building	$466 billion	$29.6 billion	6.4%
Direct Economic Loss – Business Interruption	1 x bldg. value	$36.9 billion	7.9%
Daytime Casualties - All	8,863,200	25,014	2.8/1,000
Daytime Casualties – Immediate Deaths	8,863,200	1,190	0.13/1,000

Table 8.12 includes loss ratios that are calculated as losses divided by exposure. These ratios provide a basis to compare individual building results of the AEBM example with average (or typical) losses for the study region. Comparison of loss ratios given in Table 8.12 indicate that Original Building losses exceed average losses for Los Angeles County, in part due to the higher than average level of ground shaking at the LACDPW Headquarters building site. The CO Retrofit Scheme has substantially lower loss ratios that are comparable to or less than those of Los Angeles County.

Damage-state probabilities are based on best estimates of damage considering the inherent variability of ground shaking, building capacity and damage states. Losses based on "best estimates" of damage may be thought of as "expected" losses, recognizing that actual losses could be substantially higher or lower. Direct economic loss is based on the combination of many states of damage to structural and nonstructural systems that effectively create a continuous distribution of possible dollar losses. Economic losses reported by the AEBM represent the center values of these continuous distributions.

Casualties, in particular, deaths are based on a much more discrete set of possibilities. Table 8.12 reports 9 immediate (daytime) deaths that are based on the assumption that there is a 1/3-probability of no collapse, a 1/3-probability partial (single-story) collapse and a 1/3-probability of full collapse. Full collapse is expected to immediately kill 160 people, based on the daytime population of 1,600 and the 0.10 immediate death rate given collapse (Table 8.8). Partial collapse of a single-story is expected to immediately kill 16 people, 1/10 of full collapse deaths. Thus, the expected number of immediate deaths (9 deaths) represents an approximate 5% chance (i.e., 1/3 of the 0.16 probability of Complete structural damage) of full collapse that would immediately kill 160 people and an approximate 5% chance of a single-story collapse that would immediately kill 16 people. The expected number of 9 deaths tends to understate the number of deaths that could occur if the building actually collapses.

8.5.2 Sensitivity Analyses

Users are required to input a large amount of data in the AEBM based on engineering judgement and assumptions that are inherently uncertain, and thus affect the reliability of the results. While uncertainty in capacity, fragility and loss parameters is unavoidable, the AEBM may be used to test the sensitivity of results to input parameters.

As an example of sensitivity analyses, the AEBM example is run for five different sets of Profile data:

- Default AEBM Profiles data (All Default Data)
- Default AEBM Profiles data with modified Capacity parameters (Capacity Only)
- Default AEBM Profiles data with modified Fragility parameters (Fragility Only)
- Default AEBM Profiles data with modified Loss parameters (Loss Only)
- Modified AEBM Profiles data (All Modified Data).

These AEBM example runs test the sensitivity of results to modifications of default Profile data, indicating which modifications have the greatest affect on estimated losses. Direct economic loss results are summarized in Table 8.13 for the Original Building and CO Retrofit Scheme, respectively. Table 8.13 includes a "%Δ" column that provides a measure of the change in result values when modified parameters are used in lieu of default parameters.

Table 8.13 suggests that default data produces reasonable estimates of losses for the Original Building that are only modestly different from those based on modified properties. Conversely, there are significant differences (improvements) to estimates of CO Retrofit Scheme losses when default data is modified, particularly with respect to losses to the structural system.

Table 8.13. Comparison of Economic Losses

	Total Direct Economic Loss (dollars in millions)				Structural Direct Economic Loss (dollars in millions)			
	Original Building		CO Retrofit Scheme		Original Building		CO Retrofit Scheme	
	Value	% Δ	Value	% Δ	Value	% Δ	Value	% Δ
Default Profile – *Hazus* GBS Data	$9.84		$5.37		$3.66		$1.58	
Modified Profile – Capacity Data Only	$9.85	0%	$4.18	-22%	$3.49	-5%	$1.08	-32%
Modified Profile – Fragility Data Only	$8.12	-17%	$3.47	-35%	$2.74	-25%	$0.49	-69%
Modified Profile – Loss Data Only	$14.30	+45%	$5.60	+4%	$7.44	+103%	$1.80	+14%
Modified Profile – All Data	$10.85	+10%	$2.33	-56%	$5.49	+50%	$0.33	-79%

SECTION 9

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