FEMA Benefit-Cost Analysis Re-engineering (BCAR)

Earthquake Non-Structural Full Data Module Methodology Report

Version 4.5

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Contents

Purpose

This BCAR report is provided for use by interested BCA users to review and understand the methodology behind the Federal Emergency Management Agency (FEMA) Earthquake Non-Structural Full Data Benefit-Cost Analysis (BCA) Module. The methodology report was used by the FEMA Technical Advisory Group (TAG), and is part of a larger effort to re-engineer the FEMA Benefit-Cost Analysis (BCA) methods, modules, guidance, and training in order to improve the BCA process. The goal of the BCA re-engineering process is to develop methodologies that keep the analysis process simple for the average user, while basing those methodologies on well-defined scientific and engineering principles that accurately represent structure performance before and after mitigation. The intent of the Earthquake Non-Structural Full Data Module remains the same: to conduct a BCA for an individual non-structural (acceleration-sensitive) building component using project-specific seismic hazard data and Seismic Damage Functions (SDFs) to estimate damages. This methodology report is part of a larger effort to re-engineer the FEMA BCA methods, Modules, guidance, and training in order to improve the BCA process.

Problem Statement

This section summarizes the major assumptions and equations related to the Earthquake Non-Structural Full Data Module that significantly affect typical analysis projects. Problem statements are defined for those components that need to be addressed, as identified in the BCAR Methodology Update List or during the June 2007 and September 2007 BCAR TAG Meetings. These components include the following items:

- Incorporating the latest seismic hazard data from the U.S. Geological Survey (USGS).
- Improving the soil type modification calculation.
- Investigating other sources, such as the Hazards United States (HAZUS) risk assessment software, for documented fragility curves and seismic damage functions.

There are nine different acceleration-sensitive, non-structural components considered in the existing Earthquake Non-Structural Full Data Module that each have varying input requirements. Tables 1 and 2 summarize the input parameters to be discussed throughout this report.

Table 1. Acceleration-Sensitive Non-Structural Components (Part A)

	Acceleration-Sensitive Non-Structural Component			
Input Item	**Generic Contents**	**Parapet Walls**	**Racks-Shelves**	**Generators**
Annual Operating Budget	x	x	x	x

Continuity Premium	x	x	x	x
Value of Each Component	x	x	x	x
Number of Components	x	x	x	x
Total Building Occupancy	x		x	x
Occupancy at Component Only		x		
Total Building Area	x		x	x
Fall Impact Area	x		x	x
Minor Injury Rate (in Fall Area or Component)	x	x	x	x
Major Injury Rate (in Fall Area or Component)	x	x	x	x
Casualty Rate (in Fall Area or Component)	x	x	x	x
Value of Injuries and Casualties	x	x	x	x
Damage State Percentages	x	x	x	x
Functional Downtime per Component	x	x	x	x
Support and Anchoring Parameter	x	x	x	x
Secondary Damages (Other)	x	x	x	x
Mitigation Project Cost	x	x	x	x
Project Useful Life	x	x	x	x

Table 2. Acceleration-Sensitive Non-Structural Components (Part B)

Input Item	**Acceleration-Sensitive Non-Structural Component**				
	Elevators	**Fire Sprinklers**	**HVAC**	**Ceilings**	**Electrical Cabinets**
Annual Operating Budget	x	x	x	x	x
Continuity Premium	x	x	x	x	x
Value of Each Component	x	x	x	x	x
Number of Components	x	x	x	x	x
Total Building Occupancy		x		x	x (see Note 1)
Occupancy at Component Only	x				
Total Building Area		x		x	x (see Note 1)
Fall Impact Area		x		x	x (see Note 1)
Minor Injury Rate (in Fall Area or Component)	x	x		x	x
Major Injury Rate (in Fall Area or Component)	x	x		x	x
Casualty Rate (in Fall Area or Component)	x	x		x	x
Value of Injuries and Casualties	x	x	x	x	x
Damage State Percentages	x	x	x	x	x
Functional Downtime per Component	x	x	x	x	x
Support and Anchoring Parameter	x	x	x	x	x
Secondary Damages (Other)	x	x	x	x	x
Mitigation Project Cost	x	x	x	x	x
Project Useful Life	x	x	x	x	x
Note 1: The occupancy data and area for electrical cabinets are based on the room size in which the cabinet is located.					

Overview of Benefits

The benefits of a hazard mitigation project are the expected damages (future losses) prevented or reduced by the project. The BCA counts the present value (in dollars) of the annual avoided damages over the project useful life. A BCA takes into account:

- The probabilities of various levels of natural hazard events and damages
- The useful lifetime of the mitigation project
- The time value of money (the discount rate)

To calculate benefits ($B_{Project}$), the Earthquake Non-Structural Full Data Module estimates the damages for both the before- and after-mitigation conditions at various seismic intensity levels (earthquake events) based on the annual percentage chance (probability) that a particular seismic intensity level will occur.

$$B_{Project} = \left(EAB \times PVC\right)$$

$$PVC = \frac{1-(1+r)^{-T}}{r}$$

Where:

EAB	is the total expected annual net benefit of the hazard mitigation project.
PVC	is the present value coefficient.
T	is the estimated amount of time (in years) that the mitigation action will be effective (also called the Mitigation Project Useful Life).
r	is the annual discount rate used to determine the "Net Present Value" of benefits. For FEMA-funded projects, the rate is set by the Office of Management and Budget (OMB).

The expected annual net benefit (*EAB*) is the difference between expected annual damages (EAD) before- and after-mitigation ($EAD_{Before\ Mitigation}$ and $EAD_{After\ Mitigation}$).

$$EAB = EAD_{Before\,Mitigation} - EAD_{After\ Mitigation}$$

Where:

$\boldsymbol{EAD_{Before\ Mitigation}}$	is the expected annual damages before mitigation.
$\boldsymbol{EAD_{After\ Mitigation}}$	is the expected annual damages after mitigation.

To determine the EAD, the Module multiplies the annual probability for a given seismic intensity level by the estimated (scenario) losses for a seismic intensity level. There are seven "bins" or ranges of seismic intensity levels in the form of peak ground accelerations (PGAs). PGA is the acceleration of the ground at a building site during an earthquake and is expressed in terms of a percentage of the acceleration of gravity (g). The ranges are as follows:

PGA (% g)	4-8	8-16	16-32	32-55	55-80	80-100	>100

The EAD can be expressed as:

$$EAD_{AfterMitigation} = \sum_{pga=4-8}^{pga=>100} EAD_{(pga)} = \sum_{pga=4-8}^{pga=>100} [EANEQ_{(pga)}][L_{(pga)}]$$

$$EAD_{BeforeMitigation} = \sum_{pga=4-8}^{pga=>100} EAD_{(pga)} = \sum_{pga=4-8}^{pga=>100} [EANEQ_{(pga)}][L_{(pga)}]$$

Where:

pga	is the peak ground acceleration range or "bin."
EAD(pga)	is the expected annual damage at PGA.
EANEQ(pga)	is the Expected Annual Number of Earthquakes at PGA.
L(pga)	is the expected losses or damages at PGA.

The benefit-cost ratio (BCR) is the benefits of the mitigation project ($B_{Project}$) divided by the costs ($C_{Project}$) of the mitigation project.

$$BCR = \frac{B_{Project}}{C_{Project}}$$

Where:

$B_{Project}$	is the total benefit of the hazard mitigation project over the project useful life.
$C_{Project}$	is the total net present value of the cost of the hazard mitigation project.

Mitigation Project Useful Lifetime

Description: The mitigation Project Useful Lifetime (*T*) is the estimated amount of time (in years) that a mitigation project will remain effective.

Recommendation: Values from the Project Useful Life Summary Table will be provided based upon responses to certain questions. For example:

- Non-structural major equipment (Elevators; Heating, Ventilation, and Air-Conditioning [HVAC]; and Sprinklers) = 15 years
- Non-structural minor equipment (Generic Contents, Racks and Shelves) = 5 years
- Non-structural building elements (Ceilings, Electrical Cabinets, Generators, Parapet/Chimneys) = 30 years

Documentation will be required if the recommended values are overwritten.

Changes: This recommended approach does not change the application of this variable within current BCA calculations. It does, however, set a rule governing when documentation is required.

Discount Rate

Description: The discount rate determines the time-value of money and is mandated by OMB to be 7 percent for all BCAs.

Problem: Methodology Update List Item Number V–001 requires that the BCAR effort coordinate with OMB to lower the current value. During the June 2007 TAG Meeting, it was decided that FEMA will take the lead in contacting OMB for discussions about the discount rate.

Recommendation: The discount rate will remain part of the Module. However, the analyst must provide documentation if he/she changes the default value (documentation automatically becomes a required field if the discount rate is changed). If OMB changes the discount rate, the default value will be modified in the next release of BCA software updates.

Changes: This recommended approach does not change the application of this variable within current BCA calculations.

Seismic Hazard Curve (Expected Annual Occurrence)

Description: The Seismic Hazard Curve is comprised of acceleration values representative of seven "bins" or ranges of seismic intensity, and the expected annual occurrence (probability).

Problem: Methodology Update List Item Number SNS-002 requires that the BCAR effort add the seismic hazard data and probability calculations directly into the Earthquake Non-Structural Full Data Module. Currently, users must utilize the Earthquake Structural Full Data Module to obtain seismic hazard data that can be input into the Earthquake Non-Structural Full Data Module. The seismic hazard calculator is a tool that is used to compute probabilities for the seven bins of peak ground accelerations. It is located in the FEMA BCA Toolkit Version 2.0.

Methodology Update List Item Numbers SS-005 and SS-006 require that the BCAR effort re-evaluate the probability calculations based on the most current seismic hazard data (PGA) available from USGS. The existing Earthquake Structural Full Data Module extracts PGA values from a USGS database file for three data points corresponding to the following probabilities of exceedance:

Probability of Exceedance	Return Period
10 percent chance in 50 years	475 years
5 percent chance in 50 years	975 years
2 percent chance in 50 years	2475 years

The Module computes a regression analysis fit between the logarithm of exceedance probability and PGA to obtain a smooth curve relating exceedance probability and PGA. This mathematical fit allows exceedance probabilities to be calculated for any PGA level. The problem is that extrapolation is used to determine probabilities outside the range of the three data points in the table above.

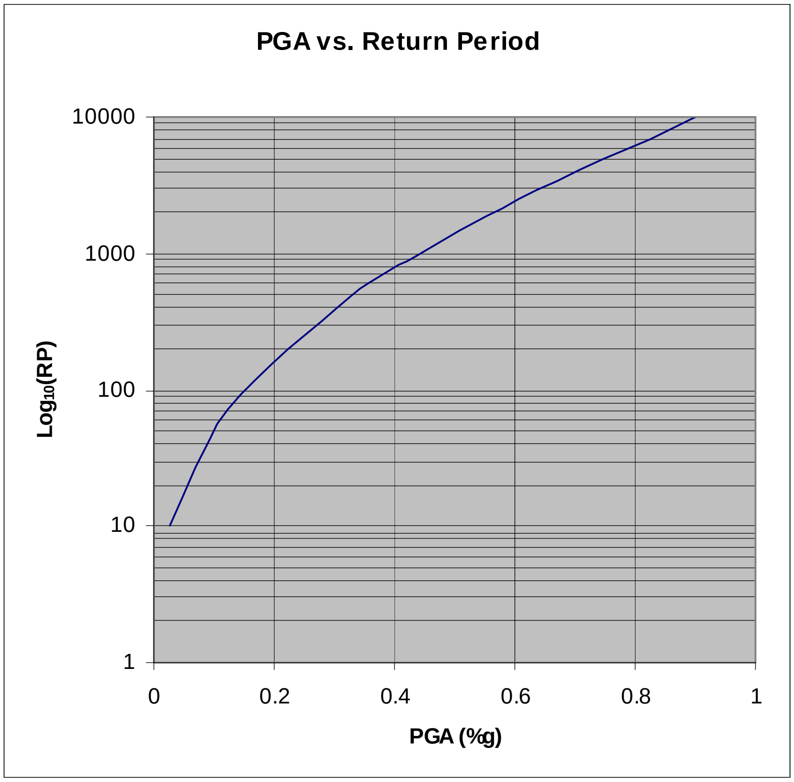
In addition, the database for the Earthquake Structural Full Data Module only contains PGA data for the contiguous 48 States. Currently, users must obtain PGA data from an outside source, such as USGS, for areas outside of the contiguous 48 States. This data must be input into a separate seismic hazard calculator (MS Excel spreadsheet) to obtain probabilities that can be input into the Earthquake Structural Full Data Module.

Recommendation: Obtain PGA values for return periods ranging from a 10-year event to the 10,000-year event for all 50 States and U.S. Territories, including Puerto Rico, the U.S. Virgin Islands, Guam, and American Samoa as they become available. This will minimize extrapolation and eliminate the need for the seismic hazard calculator.

Probability of Exceedance (in 50 years)	Return Period (Years)	PGA (g)
99 percent	10	0.0273
50 percent	72	0.1229
10 percent	475	0.3249
5 percent	975	0.4363
2 percent	2,475	0.6060
0.5 percent	10,000	0.8996

Sample USGS PGA Values for Site Class B and Zip Code 98102

For example, the six data points shown on the previous page can be plotted on a graph [PGA verses Log_{10} (RP)] and, as shown on the following table, the curve is parabolic in nature. The new software will actually use 12 data points ranging from the 10-year event to the 10,000-year event.



To calculate the probabilities for the seven bins of PGA, a parabolic interpolation between any two points on the curve is used to obtain the return period, *RP*. The return period can be converted into a probability of exceedance using the following equation:

$$EANEQ_{ipgab} = 1 - e^{(-t/RP)} \approx \frac{1}{RP}$$

Where:

***EANEQ**ipgab* — is the frequency of exceedance of the PGA of either the lower bound or upper bound of the i^{th} bin.

t — is the exposure time in years (1 year for annual frequency of occurrence).

RP — is the average return period of the PGA of either the lower bound or upper bound of the i^{th} bin.

PGA (% g)	4-8	8-16	16-32	32-55	55-80	80-100	>100

The frequency of annual occurrence for the PGA bins listed above can be calculated using the following equation:

$$\text{EANEQ}_i = \text{EANEQ}_{ipga1} - \text{EANEQ}_{ipga2}$$

Where:

EANEQ_i	is the frequency of annual occurrence for the i^{th} PGA bin.
EANEQ_{ipga1}	is the frequency of exceedance of the PGA of the lower bound of the i^{th} bin.
EANEQ_{ipga2}	is the frequency of exceedance of the PGA of the upper bound of the i^{th} bin.

Changes: The recommended approach does not change the application of the expected annual occurrence within current BCA calculations. It does, however, improve the accuracy of the probability calculations and negates the need for the seismic hazard calculator.

Soil Type Modification

Description: Soils are classified by hardness in the 1997 National Earthquake Hazards Reduction Program (NEHRP) Seismic Design Provisions and the Uniform Building Code (UBC, see *Appendix B. Classification System* table on the following page). Soil types range from site class A, which is a hard rock, to site class F, which is soft, liquefiable soil. Soft soils can amplify or de-amplify PGA depending on the level of ground shaking (see table titled *Earthquake Ground Motion Parameter Calculator version 5.0.7* on page 10 of this report). For site class F, it is recommended to remediate the site or relocate to a new site (with site class E or better) prior to pursuing an earthquake mitigation project for a structure. It is important to note that there is a modification factor for both short period spectral acceleration and long period spectral acceleration of buildings, but not for peak ground acceleration.

Appendix B. Classification Systems

Table B.1 Site Classes
(from the 1997 *NEHRP Provisions*)

Site Class	Site Class Description	Shear Wave Velocity (m/sec)	
		Minimum	**Maximum**
A	HARD ROCK Eastern United States sites only	1500	
B	ROCK	760	1500
C	VERY DENSE SOIL AND SOFT ROCK Untrained shear strength $u_s \geq 2000$ psf ($u_s \geq 100$ kPa) or $N \geq 50$ blows/ft	360	760
D	STIFF SOILS Stiff soil with undrained shear strength 1000 psf $\leq u_s \leq$ 2000 psf (50 kPa $\leq u_s \leq$ 100 kPa) or $15 \leq N \leq 50$ blows/ft	180	360
E	SOFT SOILS Profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index PI > 20, moisture content w > 40% and undrained shear strength u_s < 1000 psf (50 kPa) (N < 15 blows/ft)		180
F	SOILS REQUIRING SITE SPECIFIC EVALUATIONS 1. Soils vulnerable to potential failure or collapse under seismic loading: e.g. liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays (10 ft (3 m) or thicker layer) 3. Very high plasticity clays: (25 ft (8 m) or thicker layer with plasticity index >75) 4. Very thick soft/medium stiff clays: (120 ft (36 m) or thicker layer)		

The table above is reprinted from the HAZUS MH MR2 Earthquake Model Users Manual[1]

[1] National Earthquake Hazards Reduction Program (NEHRP), 1997 Provisions included in the HAZUS MH MR2 Earthquake Model Users Manual, Appendix B. HAZUS is a regional earthquake loss estimation software program developed by the National Institute of Building Sciences (NIBS) under contract with FEMA.

Soil Factors as Function of Site Class and Spectral Accelaration

Values of Fa as a function of Site Class and 0.2 sec MCE Spectral Acceleration

Site Class	Ss<=0.25	Ss=0.50	Ss=0.75	Ss=1.00	Ss>=1.25
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	a	a	a	a	a

The table above describes the site class modification factors for short period (0.2-second) spectral accelerations.[2]

Problem: Methodology Update List Item Number SS-002 requires that the BCAR effort re-evaluate the soil type modification calculations. PGA data from USGS is based on soil type B/C, the boundary between NEHRP classes B and C. The existing Earthquake Structural Full Data Module modifies the PGA values for rock based on the user-entered soil type and the soil type modification factors in the table above (short period modification factors). For some zip codes in conjunction with choosing soil type E, the Module has a calculation error and will not modify the PGAs.

Recommendation: Re-evaluate the calculations for the soil type modification and ensure the proper use of the soil type modification factors for short period spectral accelerations to the PGA. It is important to note that PGA values are comparable to short period spectral accelerations, and therefore it is appropriate to use the modification factors for short period spectral acceleration. The modification factor will be applied to the 12 data points extracted from the USGS database prior to interpolation as described in the previous section.

Changes: The user will still enter the soil type. The change will produce more accurate soil type modification calculations.

$$PGA_{modified} = PGA \times Fa$$

Where:

***PGA** modified*	is the modified PGA for a particular return period based on soil type (site class A through E) selected by the user.
Fa	is the short period spectral acceleration modification factor based on soil type (site class A through E) selected by the user.

[2] NEHRP 2003 Seismic Design Provisions Site Coefficients reprinted from the USGS Earthquake Ground Motion Parameter Calculator version 5.0.7 (http://earthquake.usgs.gov/research/hazmaps/design/).

Expected Damages

Description: The expected losses at specific seismic intensity levels are determined by the SDFs built into the Module. Expected losses are dependant on defining what the component is (i.e., bookshelves, mechanical equipment, parapets, elevators, etc.), as well has how the component is supported or weighted. This will be discussed in more detail later in this report.

In the Earthquake Non-Structural Full Data Module, damages are categorized as follows:

- Acceleration-Sensitive Non-Structural Damage (direct physical damage)
- Loss of Function
- Injuries (Minor and Major) and Deaths
- Other Secondary Damages

The total expected scenario damages are the sum of the damage categories.

$$L_{(pga)_{Total}} = \left(L_{(pga)_{ASN}} + L_{(pga)_{Loss\ of\ function}} + L_{(pga)_{inury/death}} + L_{(pga)_{Other}} \right)$$

Where:

$L_{(pga)ASN}$ is the expected amount of acceleration-sensitive Non-Structural damages at PGA.

$L_{(pga)Loss\ of\ function}$ is the expected amount of lost public/nonprofit service at PGA.

$L_{(pga)injury/death}$ is the expected amount of injuries and deaths resulting from non-structural damages at PGA.

$L_{(pga)Other}$ is the expected amount of secondary damages avoided at PGA.

The methodology for determining losses for each of the above categories involves defining SDFs and the non-structural component parameters that determine the SDFs.

Seismic Damage Functions (SDFs)

SDFs are used to estimate expected losses for various types of non-structural components at different seismic intensity levels (i.e., PGA range or "bin"). The PGAs for the SDFs typically range from 4 percent to over 100 percent of the acceleration of gravity, and are split into seven bins as previously discussed. The Earthquake Non-Structural Full Data Module calculates damages for these seven bins using the SDFs that were developed for each component type and support type. The non-structural component parameters and SDFs for the various loss categories are described below. Prior to detailed discussion regarding SDFs, it is important to define the non-structural component parameters that affect the development of SDFs.

Non-Structural Component Parameters

Description: Performance of non-structural components during seismic events depends on the component and the means by which that component is supported, anchored, or weighted (weight distribution). For example, a top-heavy bookshelf tends to overturn during an earthquake, whereas a bottom-weighted book shelf will tend to slide. Therefore, it is important to define these parameters in order to apply the appropriate seismic damage functions.

For example, the following list describes the anchoring and weighting condition for generic contents and equipment in the before-mitigation scenario.

Generic Contents and Equipment

- Bottom weighted equipment - unanchored
- Bottom weighted equipment - poorly anchored
- Even weighted equipment - unanchored
- Even weighted equipment - poorly anchored
- Top weighted equipment - unanchored
- Top weighted equipment - poorly anchored

Acceleration-Sensitive Non-Structural Damages

Description: Acceleration-sensitive non-structural damage involves damage to components of buildings that tend to be removed from their supports or fall over as a result of the acceleration of a building during an earthquake. Examples of acceleration-sensitive non-structural components are listed in Tables 1 and 2 on page 2 of this report.

It is important to note that this module is intended for mitigation projects that directly affect the seismic performance of the non-structural component (i.e., anchoring bookshelves or mechanical equipment), and if a non-structural mitigation project is combined with a structural mitigation project, it is possible to count benefits twice. For example, the Earthquake Structural Full Data Module accounts for damages to non-structural, acceleration-sensitive components even though the mitigation project is for the structural components of the building. If the Earthquake Non-Structural Module is used for a non-structural mitigation project in the same building, damages to that particular non-structural component would be counted twice. It is recommended to use the Earthquake Structural Full Data Module when considering both structural and non-structural retrofit in the same building. Additional details are described in the methodology report for the Earthquake Structural Full Data Module.

Problem: The existing Earthquake Non-Structural Full Data Module has default fragility curves and seismic damage functions for acceleration-sensitive components of buildings. However, the fragility curves and seismic damage functions have little or no documentation for the derivation of the functions. The fragility curves may have been developed using engineering judgment with the HAZUS fragility curves as a basis. As discussed at the September 2007 TAG meeting, the re-engineering effort will include an investigation of replacing the current fragility curves and damage functions with the actual HAZUS-based fragility curves and damage functions.

Recommendation: There are three options regarding the determination of acceleration-sensitive, non-structural damages:

1. Implement HAZUS-based fragility curves and seismic damage functions.

   These curves represent a general classification of acceleration-sensitive, non-structural components and not individual components, such as elevators, HVAC, ceiling tiles, generators, etc. As stated in the HAZUS Earthquake Technical Manual (Chapter 5, Section 5.3.2), the curves are intended for regional loss estimation and not losses to a specific non-structural component. There is insufficient data to develop fragility curves for specific non-structural components. In addition, the curves are dependent on choosing a building type and a design code level for the building, as opposed to the anchorage, support, or weight characteristics of the non-structural component. The fragility curves and damage functions are based on the before- and after-mitigation condition of the building, and not a mitigation project or retrofit to the non-structural component.

2. Continue to use the default fragility curves and seismic damage functions implemented in the existing Earthquake Non-Structural Module.

   These fragility curves are dependent on the anchorage, support, or weight distribution characteristics of non-structural building components, and not on the characteristics of the building that affect seismic performance. Therefore, the building that contains the acceleration-sensitive, non-structural component has no effect on the performance of the component. There is an underlying assumption that the building performance, which affects the performance of the non-structural component, is the same for the before- and after-mitigation scenarios. Therefore, the building performance has a negligible effect on the BCR.

3. Conduct more research to see if there are alternate sources for fragility curves and seismic damage functions for acceleration-sensitive, non-structural components.

   At this point, there is ongoing research at several universities and it does not appear that there are widely accepted fragility curves ready for implementation. In addition, the fragility curves being developed through research projects seem to be dependent on the building performance, similar to those included in HAZUS.

Based on these three options, the recommendation is to use the existing default fragility curves (Option 2) and seismic damage functions until better data is available.

Acceleration-sensitive, non-structural damages are estimated as the product of the acceleration-sensitive, non-structural SDF and the total value of the components.

$$L_{(pga)_{ASN}} = (SDF_{ASN})(V_{TotalComponent\,Value})$$

Where:

SDF $_{ASN}$	is the acceleration-sensitive, non-structural SDF, expressed as a percentage of V.
V $_{Total\ Component\ Value}$	is the total value of all components, expressed in dollars.

The acceleration-sensitive, non-structural SDF (SDF_{ASN}) is equal to the percentage associated with the type of component and the support parameters at a given seismic intensity level (PGA bin).

In order to better understand acceleration-sensitive, non-structural damages, it is prudent to further discuss the following parameters:

- Acceleration-sensitive SDFs
- Fragility curves used to develop the SDFs
- Damage States that are used to develop fragility curves
- Value of non-structural components

Acceleration-Sensitive, Non-Structural SDFs

Description: Acceleration-sensitive, non-structural damage functions are calculated from fragility curves by multiplying damage state probabilities by the damage percentage defined for a damage state. The damage percentages are "default" values included in the existing Earthquake Non-Structural Full Data Module and are based on engineering judgment.

$$SDF_{ASN} = (PROB_{DS})(PD_{DS})$$

Where:

PROB $_{DS}$	is the probability for damage state (DS) at PGA.
PD $_{DS}$	is the percent damage defined for a particular damage state (i.e., moderate, extreme)

Fragility Curves

Description: Fragility curves express the probability that a particular damage state (i.e., none, slight, moderate, extensive, and complete) will occur at a given level of earthquake demand (i.e., PGA level or bin). In the existing Earthquake Non-Structural Full Data Module, fragility curves vary markedly based on the specific non-structural component. The fragility curve probabilities ($PROB_{DS}$) are included in the existing Earthquake Non-Structural Full Data Module for each support, anchorage, and weighting condition for each bin of PGA. The probabilities were developed based on engineering judgment.

Damage States

Description: In order to develop fragility curves and seismic damage functions, descriptive damage states must be defined to characterize the extent of earthquake damage. The existing Earthquake Non-Structural Full Data Module uses damage states such as "moderate" and "extensive" for most components (i.e., generators, shelves, and elevators). One exception to this is for fire sprinklers, which have damage states of "limited" and "widespread." Sample descriptions of damage states are shown below.

Table 9.5 Examples of Non-structural Damage State Definitions

Suspended Ceilings
Slight : A few Ceiling tiles may have moved or fallen down.
Moderate: Falling of tiles is more extensive; in addition the ceiling support framing (t-bars) may disconnect and/or buckle at a few locations; lenses may fall off a few light fixtures.
Extensive: The ceiling system may exhibit extensive buckling, disconnected t-bars and falling ceiling tiles; ceiling may have partial collapse at a few locations and a few light fixtures may fall.
Complete: The ceiling system is buckled throughout and/or has fallen down and requires complete replacement.

The table above is reprinted from the HAZUS MH MR2 Earthquake Model Users Manual.[3]

The re-engineered Earthquake Non-Structural Full Data Module will use the same damage states that are defined in the existing Earthquake Non-Structural Module, since the existing fragility curves and damage functions will not change.

Value of Non-Structural Component

Description: The replacement value for labor and materials to construct a similar non-structural component in the same location.

[3] FEMA/NIBS HAZUS MH MR2 Earthquake Model Users Manual, Chapter 9.

The non-structural component value ($V_{Total\ Component\ Value}$) is determined as follows:

$$V_{TotalComponentValue} = (NSV)(components)$$

Where:

components is the number of components of the same type affected by the mitigation project.

NSV is the value of each non-structural component, expressed in dollars.

Loss of Function

Description: For buildings affected by damage to non-structural components, there may be a loss of services when a portion of the building becomes unusable following a seismic event. The value of loss of function is based on the assumption that services are worth what we pay to provide the services. The value of lost service is the product of the total value of lost services per day and the number of days of functional downtime based on the SDF. Note that the period of loss of function may be much shorter than the period of displacement necessary due to earthquake damage, because agencies will resume their functions in temporary quarters. It is also important to note that the appropriate functional downtime for non-structural projects is ONLY the marginal or additional functional downtime specifically due to failure of the non-structural items. In most cases, this functional downtime will be zero or a very small number, because the non-structural item can most likely be repaired or replaced while other repairs are being made. Typical "default" values of functional downtime based on engineering judgment are included in the existing Earthquake Non-Structural Full Data Module.

Loss of function is determined by the following equation:

$$L_{(pga)\,LossofFunction} = (SDF_{Loss\ of\ Function})(V_{Service})$$

Where:

$SDF_{Loss\ of\ Function}$ is the functional downtime SDF, expressed in days.

$V_{Service}$ is the daily Value of Service, expressed in dollars per day.

In order to determine loss of function benefits, the following parameters must be defined:

- Loss of Function SDFs
- Value of Service

Loss of Function SDF

Description: The loss of function SDF is calculated from fragility curves by multiplying damage state probabilities by the functional downtime defined for a damage state. Functional downtime values are "default" values included in the existing Earthquake Non-Structural Module and are based on engineering judgment.

The seismic damage function for loss of function is determined by the following equation:

$$SDF_{Loss\ of\ Function} = (PROB_{DS})(FD_{Per\ component})(components)$$

Where:

FD $_{Per\ component}$	is the functional downtime for damage state (DS), per component.
components	is the number of components affected by the mitigation project.

Value of Service

For information on the Value of Public Services, please see the FEMA BCAR Risk Analysis Methodology Report.

Injuries and Deaths

Description: Life safety benefits (avoided injuries and deaths) are a major component of the BCR for seismic projects and should be considered for all projects. Avoided injuries and deaths are calculated using the following equation:

$$L(pga)_{injury/death} = (SDF_{MIN} \times V_{MIN} + SDF_{MAJ} \times V_{MAJ} + SDF_{DEATH} \times V_{DEATH})(OCC_{AVG}/1000)$$

Where:

$L_{(pga)injury/death}$	is the expected amount of injuries and deaths resulting from non-structural damages at PGA.
SDF_{MIN}	is the SDF (rate) for minor injuries at PGA.
SDF_{MAJ}	is the SDF (rate) for major injuries at PGA.
SDF_{DEATH}	is the SDF (rate) for deaths at PGA.
V_{MIN}	is the value of an avoided minor injury.
V_{MAJ}	is the value of an avoided major injury.
V_{DEATH}	is the value of an avoided death.

OCC_{AVG} is the average occupancy of the building or the area affected by the component (for elevators and parapets).

In order to determine life-safety benefits, the following parameters must be defined:

- Injury and death SDFs
- Injury and death rates used to develop SDFs
- Total building occupancy
- Total building floor area
- Fall impact area used in conjunction with the total building floor area and total building occupancy to determine the number of affected occupants
- Value of avoided injuries and death

Injury and Death SDFs

<u>*Description*</u>: The injury and death SDFs are rates that are multiplied by the occupancy data and value of avoided injuries/deaths to compute scenario damages using the following equations:

$$SDF_{MIN} = (MINFA \times PAA)$$

$$SDF_{MAJ} = (MAJFA \times PAA)$$

$$SDF_{DEATH} = (DTHFA \times PAA)$$

Where:

MINFA is the probabilistic rate for minor injuries in the building at PGA.

MAJFA is the probabilistic rate for major injuries in the building at PGA.

DTHFA is the probabilistic rate for deaths in the building at peak PGA.

PAA is the percent area affected by the damaged component.

$$MINFA = (MINR \times PROB_{DS})$$

$$MAJFA = (MAJR \times PROB_{DS})$$

$$DTHFA = (DR \times PROB_{DS})$$

Where:

MINR	is the rate for minor injuries in the fall impact area at damage state, DS.
MAJR	is the rate for major injuries in the fall impact area at damage state, DS.
DR	is the rate for deaths in the fall impact area at damage state, DS.
$PROB_{DS}$	is probability for a damage state to occur at PGA.

Injury and Death Rates

Description: Rates for minor injuries, major injuries, and deaths in the fall impact area or area affected by the damaged component must be input into the module by the user. The rates are input for each damage state (i.e., moderate, extensive) that is considered in the analysis. Typical "default" rates are included in the existing modules and are based on engineering judgment. The user can override these "default" values with reasonable estimates also based on engineering judgment. The input variables are as follows:

MINR	is the minor injury rate per 1,000 occupants (at each damage state) for the fall impact area or area affected by the damaged component.
MAJR	is the major injury rate per 1,000 occupants (at each damage state) for the fall area or area affected by the damaged component.
DR	is the death rate per 1,000 occupants (at each damage state) for the fall area or area affected by the damaged component.

Total Building Occupancy

Description: The total building occupancy is the number of persons (employees and visitors) present in the building during the day, evening, and night for weekdays and weekends. The existing Earthquake Non-Structural Module calculates the average building occupancy over a 24-hour, 7-day per week period, for a total of 168 hours each week. The occupancy for the entire building is used in conjunction with the fall impact area and the total building area to determine the number of occupants that are affected in the fall impact area.

Building occupancy is determined using the following equation.

$$OCC_{Avg} = \left[\sum_{weekday+weekend} (OCC \times D \times H \times M) \right] / (7 days / week \times 24 hours / day \times 12 months / year)$$

Where:

- $\boldsymbol{OCC_{Avg}}$ is the average building occupancy over 24 hours per day, 7 days per week.
- ***OCC*** is the number of building occupants for a particular period (i.e., daytime, evening, or night) of the day (i.e., weekdays or weekends).
- ***D*** is the number of days the building has occupancy data. This value is typically 5 for weekdays and 2 for weekends, but could be less depending on the function of the building.
- ***H*** is the number of hours in a particular period. A typical value is 8 per 24 hour period for day, evening, or night.
- ***M*** Is the number of months per year the building has occupancy data. This value is typically 12, but may be less for buildings such as schools.

Occupancy at Component Only

Description: For two components (parapet walls and elevators) the occupancy data for the entire building is irrelevant, and therefore the occupancy data entry is for the area affected by the component only. For parapet walls (including chimneys), the occupancy data is only the number of people that are likely to be populating the area below the parapet walls. For elevators, the occupancy data is only the number of people in the elevator, which cannot exceed the occupancy limit of the elevator. In addition, the occupancy data for the electrical cabinet component is for the room containing the equipment, and not the entire building. The input data table and equations for these three components are the same as those used for total building occupancy.

Total Building Floor Area

Description: The total building floor area (*BFA*) is defined as the total enclosed area of the building used in conjunction with the occupancy data and fall impact area to determine expected injuries and casualties from various potential seismic events.

Fall Impact Area

Description: The fall impact area (*FIA*) is defined as the area local to the non-structural component that is likely to be affected by the impact of the component. Using a bookshelf as an example, the fall impact area is the area in which the bookshelf will fall. The fall impact area is used in conjunction with the occupancy data and building floor area to determine expected injuries and casualties from various potential seismic events.

Use the following equation to determine the percent area affected (*PAA*) by the damaged component:

$$PAA = (FIA)/(BFA)$$

Where:

FIA Is the fall impact area, expressed in square feet.

BFA is the total building floor area, expressed in square feet.

It is important to note the following exceptions:

- For elevators and parapets, the fall impact area and the total building floor area are not necessary since the occupancy data is based on the component area and not the entire building. Therefore, the *PAA* value for these two components is 100 percent.
- For the HVAC component, the fall impact and total building floor areas are also not necessary, since casualties are not considered.
- For electrical cabinets, the input value for the building floor area should be for the room containing the electrical cabinet, since the occupancy data is based on the room itself and not the entire building.

Value of Avoided Injuries and Deaths

Description: The economic value assigned to avoided minor injuries, major injuries, and deaths.

Problem: The existing Earthquake Non-Structural Module defines three severity categories (i.e., minor injuries, major injuries, and deaths). Minor injuries are defined as those requiring medical treatment, excluding minor bruises or scrapes. Major injuries are defined as those requiring hospitalization for treatment. These categories don’t correspond to the four HAZUS classifications that have been recommended for implementation in the re-engineered BCA modules.

Recommendation: Adapt the four injury severity classifications that are defined in HAZUS (see the *Injury Classification Scale* table below) so that they can be used in conjunction with SDFs from the existing

Earthquake Non-Structural Module. In other words, the four HAZUS classifications must be consolidated into three classifications.

Changes: The input remains the same: the user must input the occupancy data.

Table 9.8 Injury Classification Scale

Injury Severity	Injury Description
Severity 1	Injuries requiring basic medical aid without requiring hospitalization
Severity 2	Injuries requiring a greater degree of medical care and hospitalization, but not expected to progress to a life threatening status
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. The majority of these injuries are a result of structural collapse and subsequent collapse or impairment of the occupants.
Severity 4	Instantaneously killed or mortally injured

The table above is reprinted from the HAZUS MH MR2 Earthquake Model Users Manual.[4]

The following table defines the value assigned for each HAZUS-severity level and describes the corresponding category that is used in the existing Earthquake Non-Structural Full Data Module. It is important to note that based on an assessment by the risk analysis team, the major injury category has been combined as the average of Severity Levels 2 and 3.

Values for Injuries and Deaths

HAZUS Category	Value for HAZUS Category	Earthquake Non-Structural Module Category	Value for Non-Structural Module Category
Severity 1	$7,044	Minor Injury, V_{MIN}	$12,000
Severity 2	$128,554	Major Injury, V_{MAJ}	$1,483,750
Severity 3	$1,672,963		
Severity 4	$3,522,027	Death, V_{DEATH}	$5,800,000

[4] FEMA/NIBS HAZUS MH MR2 Earthquake Model Users Manual, Chapter 9.

Other (Secondary Damages)

Description: The "other" category includes other benefits (secondary damages) that have not been covered by the basic Earthquake Non-Structural Full Data Module, but are allowed based on FEMA's *What Is a Benefit?* publication. Quantified damages must be associated with a seismic intensity level (i.e., PGA). This interface will allow the user to relate secondary damage data with his/her analysis/structure, as long as the benefit is in an accepted category in *What Is a Benefit?* and can be associated with a seismic intensity level.

$$L_{(pga)_{Other}}$$

Where:

$L_{(pga)Other}$ is the expected amount of other (secondary) damages avoided at PGA.