FEMA Benefit-Cost Analysis Re-engineering (BCAR)

Earthquake Structural Full Data Module

Improved Building Vulnerability Relationships – Empirical Implementation of HAZUS-MH

Modification to Impose the "Equal-Displacements Rule"

FINAL

Version 4.5

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Purpose

This report is submitted to the FEMA Technical Advisory Group (TAG) to document the approved methodology for the re-engineering of FEMA Earthquake Structural Full Data Benefit-Cost Analysis (BCA) Modules. The goal was to develop methodologies that keep the analysis process as simple as possible for the user**, while basing those methodologies on more accurate, well-defined scientific and engineering principles that accurately represent structure performance before- and after-mitigation. The intent of the Earthquake Structural Full Data Module remains the same: to conduct a BCA for an individual structure utilizing project-specific seismic hazard data and damage relationships (Seismic Damage Functions [SDFs]) to estimate damages. The content of this report addresses an improved methodology for estimating damages to buildings compared to what is currently used in the existing Earthquake Structural Full Data Module. This Methodology Update Report includes a complete discussion of each element of the module (i.e., damage, loss of function, injuries and deaths, etc.) to document the theory and demonstrate the features and performance of the new module.

** For structural retrofit, the user is assumed to have the direct assistance of a Professional Engineer (Civil or Structural) who is experienced in the design of buildings to resist seismic loadings in accordance with current design codes (e.g., IBC 2006) and seismic rehabilitation guidelines (i.e., ASCE 31-03; ASCE 41-06; FEMA 547/2006 Edition).

Limitations in Previous Methodology

Restrictions: The previous Earthquake Full Data Module had default fragility (vulnerability) curves and SDFs that were based on choosing one of 36 model building sub-types (refer to Table 1 on the following page) as well as, one of four design code levels that are defined in HAZUS. The four design code levels are pre-code, low-code, moderate-code, and high code. The code level is used to describe the seismic code provisions that may have been implemented during the design of a building. Further, all structures within a particular height class (low-rise, mid-rise, and high-rise) were treated identically. In other words, a 1-story and a 3-story building of the same model building type and design level would show identical loss characteristics. Similarly, an 8-story and an 88-story building were both simple "high-rise." Characterizing a building's seismic performance based on the defined building types and an arbitrary code level is qualitative and imprecise, even for a Structural Engineer experienced in seismic analysis and design. Improper choice of the building type or design code level could either substantially over- or under-estimate seismic damages and avoided losses. In any event, accurate modeling of vulnerability pre- and post-retrofit was difficult, so the resulting benefit-to-cost ratios were often inaccurate.

Solution: Defining the building parameters remains a part of the module, but the parameters input into the module are now much more specific to the building in question, both pre- and post-retrofit. The new module simplifies the model building types to 15, and then asks the user to define the actual number of stories and the dynamic properties of a building (the design strength, fundamental elastic period, damping, and structural and nonstructural damage thresholds) instead of simply defining the building type and code level. This allows accurate modeling of vulnerability both pre- and post-retrofit, with improved accuracy of the benefit-cost analysis results. The following report is a complete discussion of the methodology.

Table 1: Model Building Types

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

The table above is reprinted from the HAZUS MH MR3 Technical Manual

Introduction

For benefit-cost analysis (BCA) to demonstrate the cost-effectiveness of seismic retrofit, applicants for FEMA mitigation grants need rapid methods to predict building performance in earthquakes. In the Benefit Cost Analysis Reengineering project (BCAR), we develop a simple framework for the evaluation of the cost to repair building damage, using engineering parameters related to seismic building codes. Specifically, relationships for building damage repair cost are found as a function of structural period, T, ground shaking spectral acceleration (Sa at elastic structural period, Te), design base shear (Cs, or V/W), ductility, height, and framing system. We rely upon these parameters to design safe buildings. These same parameters now serve for simple damage prediction, and to estimate reductions in damage afforded by seismic retrofit. This framework provides a flexible system for collecting and evaluating building damage from ground shaking, predicting earthquake damage repair costs to buildings before- and after-mitigation (i.e., retrofit), in a wide variety of seismic environments. HAZUS damage relationships are used for the damage model.

With permission from NIBS, PBS&J provided computer source code for the seismic modules of HAZUS-MH to URS for the execution of this work.

NIBS' HAZUS Earthquake Damage Model

In the 1990's the National Institute of Building Sciences (NIBS) undertook a project to develop a regional earthquake risk assessment technology. The product that emerged was HAZUS, now known as HAZUS-MH (where MH stands for 'multi-hazard'). In this BCAR task, we relate specified HAZUS inputs to damage outputs in order to extract a general damage model. URS implies no specific endorsement of HAZUS.

The HAZUS earthquake model separates damage into four discrete types:

- **Drift-Sensitive Structural Damage:** The damage to the building structural frame associated with the inter-story displacements (drifts) in a building undergoing earthquake ground motions.
- **Drift-Sensitive Non-structural Damage:** The damage to the architectural components spanning from floor-to-floor (e.g., partitions and cladding) caused by drifts in a building undergoing earthquake ground motions.
- **Acceleration-Sensitive Non-structural Damage:** the damage to the building service equipment and architectural components associated with floor accelerations in a building undergoing earthquake ground motions.
- **Contents Damage:** the damage to the contents (furnishings, office equipment, etc.) associated with floor accelerations in a building undergoing earthquake ground motions.

It is important to note that the BCA framework implemented in the Earthquake Structural Full Data Module applies to mitigation projects specifically dealing with retrofit to structural and nonstructural components of buildings even though the HAZUS model predicts damage for contents as well. Damage to contents, as defined above, is not considered in the Earthquake Structural Full Data Module since a mitigation project specific to a contents item (i.e., anchoring office equipment), may not have the detailed information required to define the building structure. BCA for mitigation projects specific to

acceleration-sensitive contents as well as nonstructural components in buildings not considered for structural retrofit should use the Earthquake Non-structural Full Data Module.

Figure 1 shows typical HAZUS curves for the first three elements of damage. Drift-sensitive structural damage, drift-sensitive non-structural damage, and acceleration-sensitive nonstructural damage are plotted as function of the spectral acceleration of the ground motion at the fundamental period of the building. The curves were developed using the Advanced Engineering Building Module of HAZUS-MH. For the example, we chose the W1 small wood-frame building type, and moderate duration of shaking (Table 5-18 of the HAZUS-MH Technical Manual).

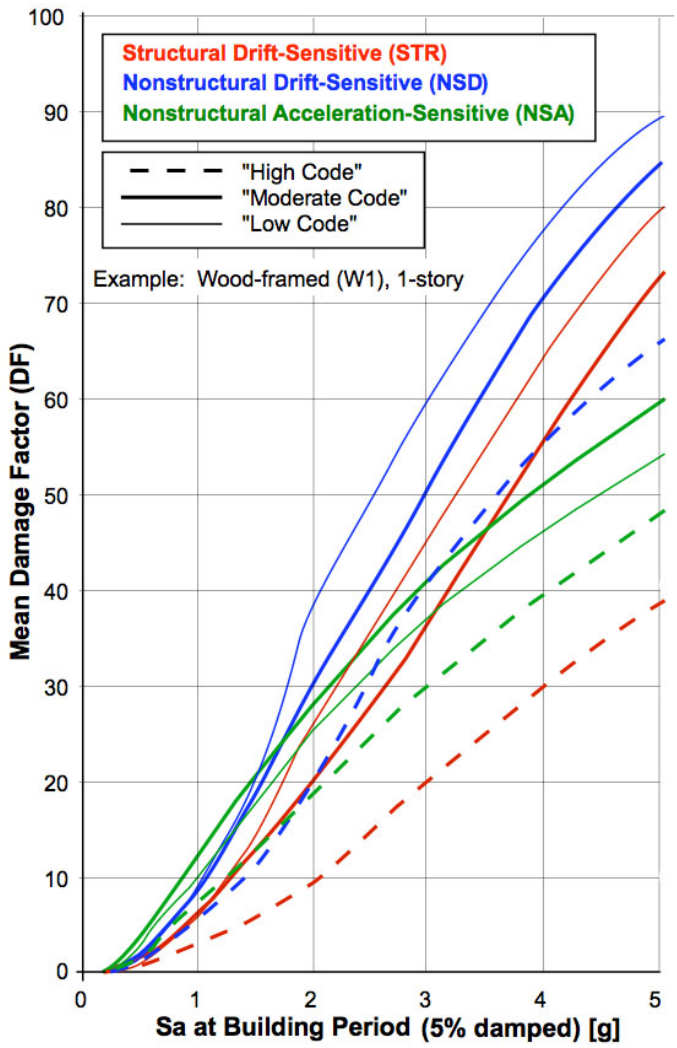

Figure 1: Typical HAZUS Earthquake Damage Relationships

HAZUS models for building damage in earthquake are designated by structural classes (model building type), occupancy class and seismic design level: high-code, moderate-code, low-code, and pre-code. While the seismic design levels are suited to HAZUS' original purpose – to model an entire regional building inventory for evaluating the impacts of earthquake scenarios on the region – the design levels do not adequately describe the seismic response of particular individual buildings pre- and post-retrofit.

For this purpose, we employ HAZUS damage models, so that damage is a function of engineering parameters:

- Model building type (e.g., W1, C2, S3, RM1, etc.)
- Elastic structural period (Te) [seconds]
- Actual strength or effective base shear (Cs or V/W) [LRFD]
- Kappa (related to hysteretic degradation)
- Drift and acceleration damage thresholds
- μ-factor (ratio of ultimate displacement to scaled yield displacement)

To provide the appropriate parameters for accurate benefit-cost analysis, it is important to understand the HAZUS framework.

The Capacity Spectrum Method depicts earthquake demand and structural capacity within the acceleration-displacement response spectrum (ADRS) format – spectral acceleration (Sa) vs. spectral displacement (Sd) [Freeman, 11ECEE, 1998].

The ground motion spectrum is transformed into a demand spectrum, accounting for structural damping and hysteretic energy dissipation. A 5% damped code-type ground motion spectrum is converted to a demand spectrum with adjustment for site soils, for structural damping other than 5%, and further reduction (Ra, Rv) for hysteretic energy dissipation modeled as equivalent viscous damping.

$$\text{Short-period demand} = Ss \times F_A / R_A$$

$$\text{Long-period demand} = S_1/T \times F_V / R_V$$

The force-displacement behavior of the building is depicted within this framework by a 'capacity curve' as shown in Figure 2 below. For the present purpose, it is sufficient to know that in the Capacity Spectrum Method, a single-degree-of-freedom (SDOF) oscillator idealizes the building's earthquake response. Sd represents the lateral displacement of the oscillator, and Sa represents the lateral force per unit of seismic mass. Radial lines from the origin (Sa=0, Sd=0) represent periods of oscillation. The capacity curve (see Figure 2) is fundamental to HAZUS. HAZUS simplifies the capacity curve to have a linear elastic part, a fully plastic plateau, and an elliptical transition between the two. The capacity curve is a simple pushover curve, translated into ADRS format. The HAZUS-MH Technical Manual, ASCE 41-06 and ATC-40 Chapter 8 describe how a nonlinear static procedure can be used to compute a pushover curve, which may then be translated into the ADRS format as a capacity curve. The capacity curve is defined for any building by (Dy, Ay) and (Du, Au). The elastic period (Te) of the structure is determined when (Dy, Ay) are determined: $Te \approx 0.32\ SQRT\{Dy/Ay\}$

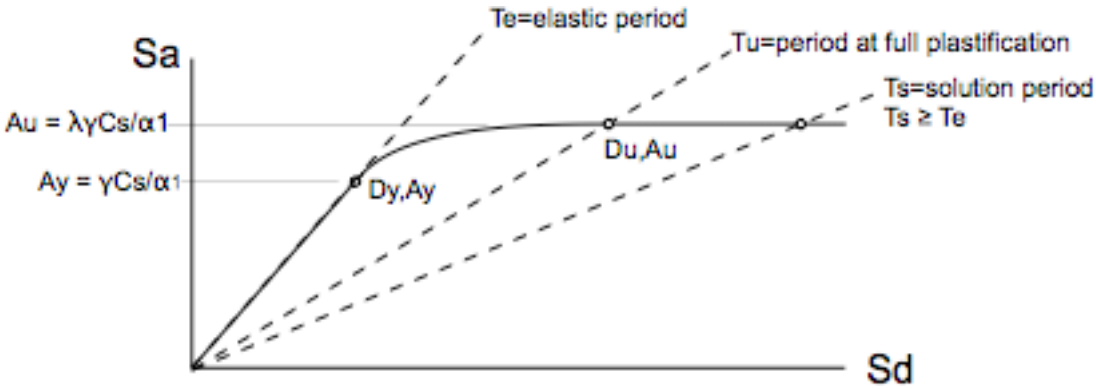

Figure 2: Capacity Curve

Te – fundamental period of the structure in its elastic response, in (seconds)

Cs – design-level base shear, in terms of load-and-resistance-factor design (LRFD)

$\alpha 1$ – the fraction of building weight effective in the pushover mode,

$\alpha 2$ – the fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement (not shown in Figure 2),

γ – an "overstrength" factor relating "true" yield strength to design strength,

λ – an "overstrength" factor relating ultimate strength to yield strength, and

μ – a "ductility" ratio relating displacement at full plastification to lambda times the yield displacement (i.e., assumed point of significant yielding of the structure).

In our adaptation of the HAZUS technology for BCA, we further simplify so that only the elastic period (Te) and design strength (Cs) are needed to define the curve. Selection of a model building type, number of stories, and code level (high code, moderate code, low code or pre-code) sets the other parameters ($\alpha 1$, $\alpha 2$, γ, λ $\alpha \nu \delta$ $\propto$).

All that HAZUS does is find a solution or performance point (Sd, Sa) along the pushover curve.

The solution point is found where the demand spectrum intersects with the capacity curve in ADRS space. This is the displacement of the equivalent SDOF oscillator. Since the hysteretic damping is a function of the performance point (and degradation, controlled by Kappa), the solution is an iterative process. Refer to HAZUS-MH Technical Manual Equations 5-7, 5-8, 5-9, and 5-10, reproduced below, as well as publications by S. Freeman and C. Kircher.

$$R_A = 2.12/(3.21 - 0.68\ln(B_{eff})) \quad (5\text{-}7)$$

$$R_V = 1.65/(2.31 - 0.41\ln(B_{eff})) \quad (5\text{-}8)$$

for which effective damping is defined as the sum of elastic damping, B_E, and hysteretic damping, B_H:

$$B_{eff} = B_E + B_H \quad (5\text{-}9)$$

Elastic damping, B_E, is dependent on structure type and is based on the recommendations of Newmark & Hall for materials at or just below their yield point. Hysteretic damping, B_H, is dependent on the amplitude of response and is based on the area enclosed by the hysteresis loop, considering potential degradation of energy-absorption capacity of the structure during cyclic earthquake load. Effective damping, B_{eff}, is also a function of the amplitude of response (e.g., peak displacement), as expressed in Equation (5-10):

$$B_{eff} = B_E + \kappa \cdot \left(\frac{\text{Area}}{2\pi \cdot D \cdot A}\right) \quad (5\text{-}10)$$

where:

- B_E is the elastic (pre-yield) damping of the model building type
- 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
- D is the peak displacement response of the push-over curve,
- A is the peak acceleration response at peak displacement, D
- κ is a degradation factor that defines the effective amount of hysteretic damping as a function of earthquake duration, as specified in Table 5.18.

Excerpt from HAZUS-MH Technical Manual Chapter 5

Once the HAZUS solution point (Sd, Sa) is determined, the damage to each part (SRT, NSD, NSA) emerges from drift-to-damage correlations and acceleration-to-damage correlations.

Magnitude Dependency

The Kappa factor depends (among other things) on earthquake magnitude, so HAZUS solutions are magnitude dependent (see Table 5-18 of the HAZUS-MH Technical Manual). High-magnitude earthquakes may subject structures to many cycles of inelastic loading, degrading the strength and stiffness of the structure, increasing the structural drifts, and hence the drift-sensitive structural and non-structural damage. In HAZUS, a high Kappa factor (>0.6) indicates full, stable hysteretic loops. Low Kappa factors (<0.4) indicate stiffness- or strength-degrading hysteretic loops with pinching. The degradation of the hysteretic loops varies with the number of large inelastic excursions, and so with the intensity and duration of ground motions.

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 of the HAZUS-MH Technical Manual.

In the present implementation, we set an initial Kappa value in accordance with the building model type and design level, but allow the knowledgeable user to adjust Kappa to be consistent with pre- and post-retrofit detailing.

Empirical Solution to HAZUS

Need for an Empirical Solution

The present release of the BCA tools does not directly execute HAZUS-MH, for the following reasons:

1. In the present version of HAZUS-MH, the routine to find the solution point (Sa, Sd) has errors that affect many of the solutions in the velocity-controlled part of the spectrum, especially for high-Kappa cases. While this may not strongly affect aggregate losses within a large group of buildings (i.e., a "portfolio"), until these issues are resolved and a stable solution is available for particular buildings, HAZUS-MH cannot be used reliably for any particular building, pre- or post-retrofit.

2. The HAZUS solution is iterative and occasionally unstable. For these BCA tools, we use a non-iterative, unconditionally stable solution to improve reliability.

3. Under some conditions (high Kappa solutions in the velocity-controlled part of the spectrum) theoretically correct Capacity-Spectrum solutions can violate the "equal-displacements rule," which implies that (all other factors being equal) increasing the strength of the SDOF oscillator results in equal or smaller oscillator displacements. Without the imposition of this rule, increasing the strength of a building (without change to stiffness, Kappa or other factors) can actually result in <u>increased</u> structural damage, contrary to accepted structural engineering logic.

Approach to the Empirical Solution

We have treated HAZUS results as "data," and we examined the relationships between the inputs and the outputs. Our goal was to extract general relationships that provide the solution point (Sd, Sa) as a function of engineering parameters (i.e., the actual strength, stiffness, ductility, and height) for any particular building, rather than using pre-set "design levels" and pre-set capacity curves representing some fictitious "average" building within a particular class. In seeking general solution behaviors, we chose to non-dimensionalize the solution space. As our "x-axis," we use a Demand-to-Capacity Ratio (DCR). As our "y-axis," we use a Ts/Te, the ratio of the solution period to the elastic period. Note, that the solution period cannot be shorter than the elastic period, so Ts/Te is greater than or equal to one. Solutions within this "solution space" are parameterized by Kappa and elastic damping.

Demand – We specify ground motion demand at the structure's elastic period, Te, using Ss and S1 adjusted to the site soil condition (Table 4.9 of the Technical Manual) and the value of damping for the particular structural system (including supplemental damping, if appropriate). A code-type spectral shape is imposed, with an acceleration-controlled region (Sa = Ss), a velocity controlled region (Sa =

S1/Te), and a constant displacement region (Sd constant = $S1/T_{VD}$) where T_{VD} is given by Equation 4.4 in the HAZUS-MH Technical Manual:

$$T_{VD} = 10^{[(M-5)/2]}$$

We segregate the solutions in each part of the spectrum ('short period' where Sa=Ss, and 'long period' where Sa=S1/Te), to avoid the imposition of fixed Ss/S1 ratios (e.g., Table 4.2; HAZUS-MH Technical Manual).

Capacity – We chose *Au*, the maximum of the capacity curve, as the capacity parameter to use in normalizing demand-to-capacity. *Au* is related to design level, *Cs,* through the overstrength factors *(γ, λ),* and to *α1,* the fraction of building weight effective in the push-over mode. To obtain the DCR, we normalize "Demand" by *Au.*

DCR = Ss/Au (Short-period solution)

DCR = S1/(Te Au) (Long-period solution)

where:

Ss = 0.3-second spectral acceleration [g] adjusted for the site Soil Profile Class, for the elastic structural damping (5%, 7%, 10%, 15%, etc.)
Ss = Sa(T=0.3s, 5%) Fa / Rae
where Rae = 2.12/(3.21 - 0.68 ln(βe)) where βe = elastic damping

S1 = 1-second spectral acceleration [g] adjusted for the site Soil Profile Class, for the elastic structural damping (5%, 7%, 10%, 15%, etc.)
S1 = Sa(T=1s, 5%) Fv / Rve
where Rve = 1.65/(2.31 - 0.41 ln(βe)) where βe = elastic damping

Te = Elastic structural period, as used in capacity-spectrum method

Au = Cs γ λ /α1 = Capacity curve maximum value [g]

HAZUS-MH was run for each Model Building Type for a range of Ss, S1 and Kappa's of interest, and solution periods (Ts) were obtained. Plotting Ts/Te versus DCR, a family of HAZUS solutions emerges, parameterized by Kappa and elastic damping. See Figures 4 and 5.

With the selected DCRs, the various design levels coalesce within each solution (short period and long period). HAZUS produces identical curves from high, moderate or low-code runs, for high, medium and low-rise, and for all Model Building Types. The plots are shown in Figures 4 and 5. The smooth behavior of the Ts/Te plots results from the simplified shape of the capacity curve and the smooth behavior of the demand curve using the 1/T code-type spectral shape. "Real" spectra and are quite irregular in shape and "real" pushover curves can be more complex. These would produce much more erratic Ts/Te curves.

To complete the empirical solution, we developed equations that approximate the lines in the data plots, so that for any DCR, we can find the Ts/Te ratio HAZUS would provide.

Note that for very long-period structures ($Ts>T_{VD}$), the demand curve transitions to constant displacement. This provides an upper bound to Sd in the HAZUS solution.

Using the Ts/Te Curve and Capacity Curve to Obtain Performance Point (Sd, Sa)

The Ts/Te solution plots and the capacity curve together provide a complete solution for the nonlinear behavior and Kappa (magnitude/duration) dependence in HAZUS. For short-period (low-rise) structures, we compute the two DCRs and (using the solution plots) we find Ts/Te and hence Ts in each solution. The shorter of the two Ts solutions "controls" (i.e., provides the correct solution). We next use the capacity curve (Figure 3) find (Sd, Sa) of the performance point along Ts. Subsequently, we can make use of the performance-point Sd and Sa to obtain the structural drift-sensitive, nonstructural drift-sensitive, and nonstructural acceleration-sensitive damage factors. For longer period structures (mid-rise and high-rise), we only compute the long-period DCR and use the long-period solution.

In this form, the HAZUS solution is unconditionally stable, non-iterative, and building specific. It matches HAZUS very well for Ts/Te > sqrt (μ). This is the fully plastic response.

At the point of full plastification (Du, Au): Ts/Te = SQRT [(Du Ay) / (Dy Au)] = sqrt(μ)

Some approximation occurs for Ts/Te < sqrt(μ), within the elastic-plastic transition. We manage fit the solutions in this transitional region with a simple spline interpolation. We note that, within HAZUS, the capacity curve uses an elliptical transition as an approximation of any building's actual capacity curve shape.

We note that the "generic" solution plots (Ts/Te versus DCR) do not depend on height class, design level, earthquake magnitude, site class or Building Model Type. By using separate long-period and short-period solutions, we can accommodate any design-type spectral shape describing site ground motions.

The solution space reveals the fundamental behavior of the HAZUS implementation of the Capacity Spectrum Method, predicting the degree of period lengthening associated with inelastic response.

The solution implies that for a given DCR and Kappa, the proportion of period lengthening is fixed. Roughly speaking, for a Zone 3 building in a Zone 3 motion, the ratio of Ts to Te is the same as for a Zone 4 building in a Zone 4 motion. The corresponding drifts (and hence damage) depend on the particulars of the capacity curve for each.

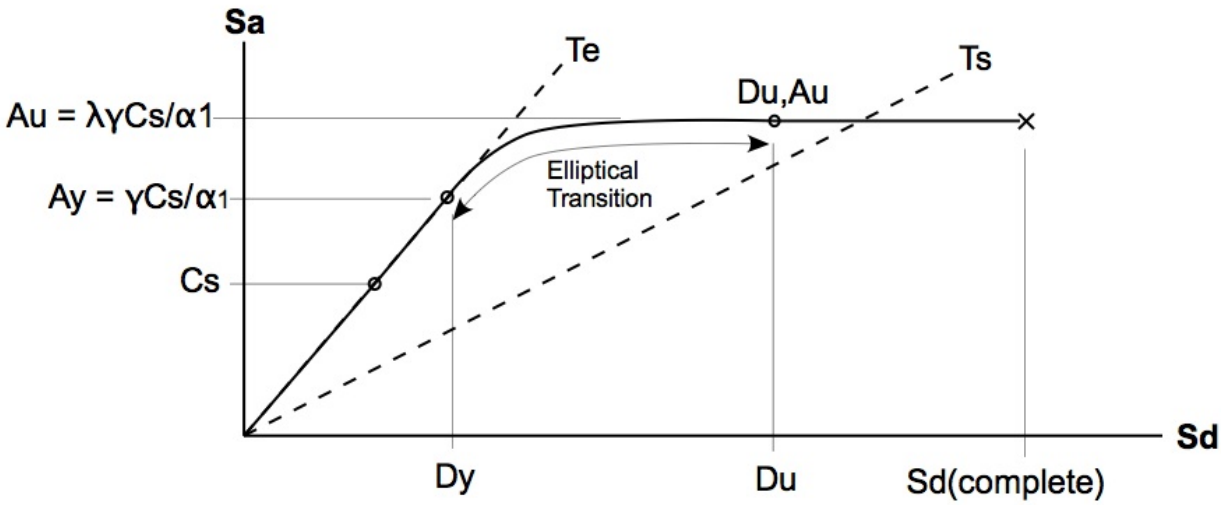

Figure 3: Capacity Curve

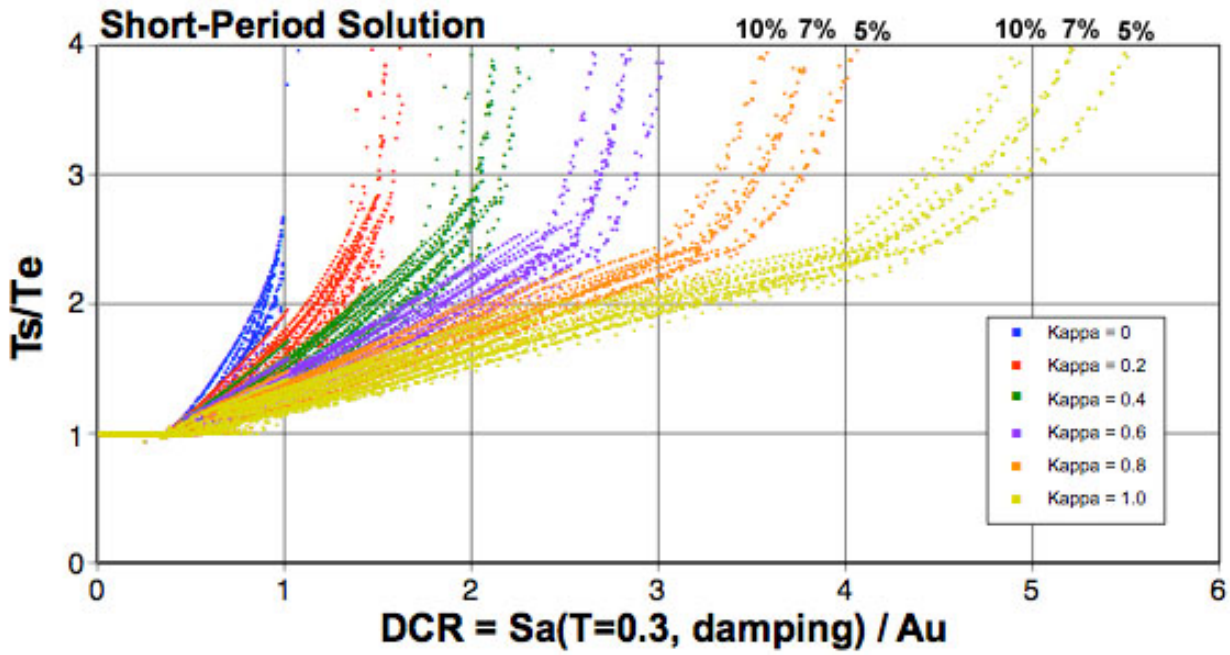

Figure 4: "Short-Period" Solutions to HAZUS

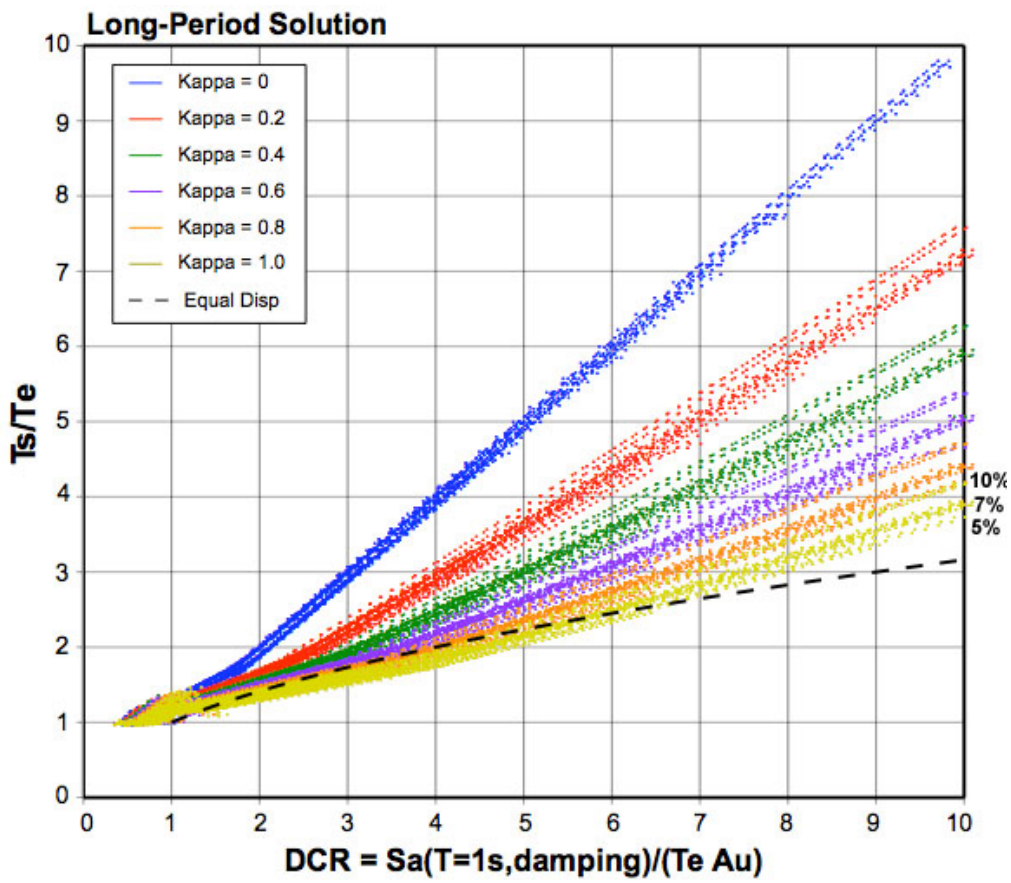

Figure 5: "Long-Period" Solutions to HAZUS

Flexible Application

The resulting damage model offers simplicity and "elegance" [Taylor, VanMarcke, et al, 1998]. It is easy to understand and apply. The input is directly in terms of engineering parameters (Te, Cs, damping, drift and acceleration limits), using familiar building code definitions. (Only Kappa is unfamiliar.) Damage relationships can be readily computed and inspected. They do not require advanced analysis methods nor are estimates of the parameters costly to develop. The models are clear for a Professional Engineer (Civil or Structural) to use in new design and in retrofit design.

Special Case – Bi-linear Capacity Curve ($\mu = \lambda = 1.0$)

The special case of a bi-linear capacity curve occurs when the elliptical transition from elastic behavior to full plastification is omitted. In terms of HAZUS parameters, this corresponds to the case for Ay=Au, Dy=Du, or $\mu = \lambda = 1.0$. This case eliminates all of the complex geometry associated with the elliptical transition.

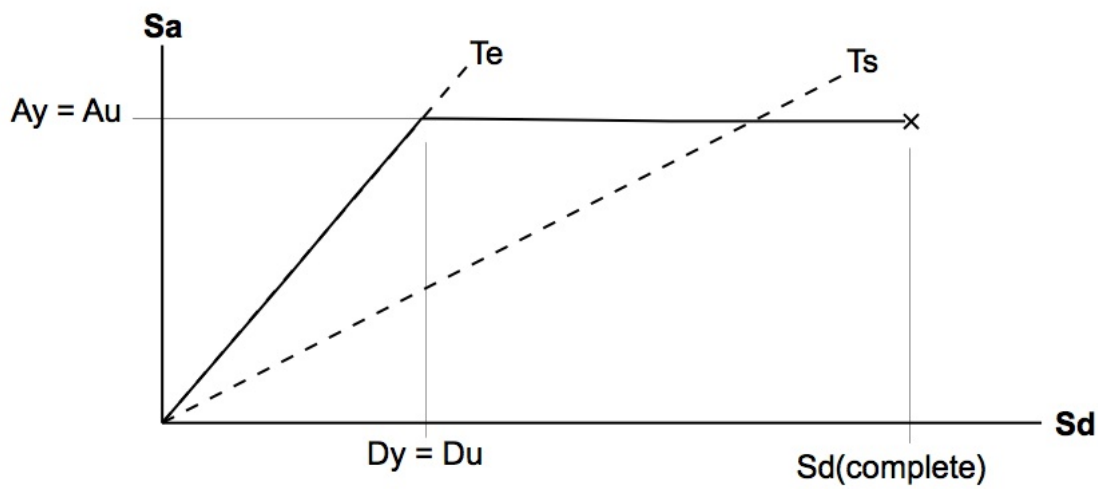

Figure 6: Bi-Linear Capacity Curve

Our empirical solutions for the special case are plotted in Figure 7 and 8 below. The curves for period lengthening are color-coded according to Kappa value. Each Kappa value has 4 separate curves, depending on the elastic damping associated with the building type. The order in which the different dampings occur is labeled in one case for clarity.

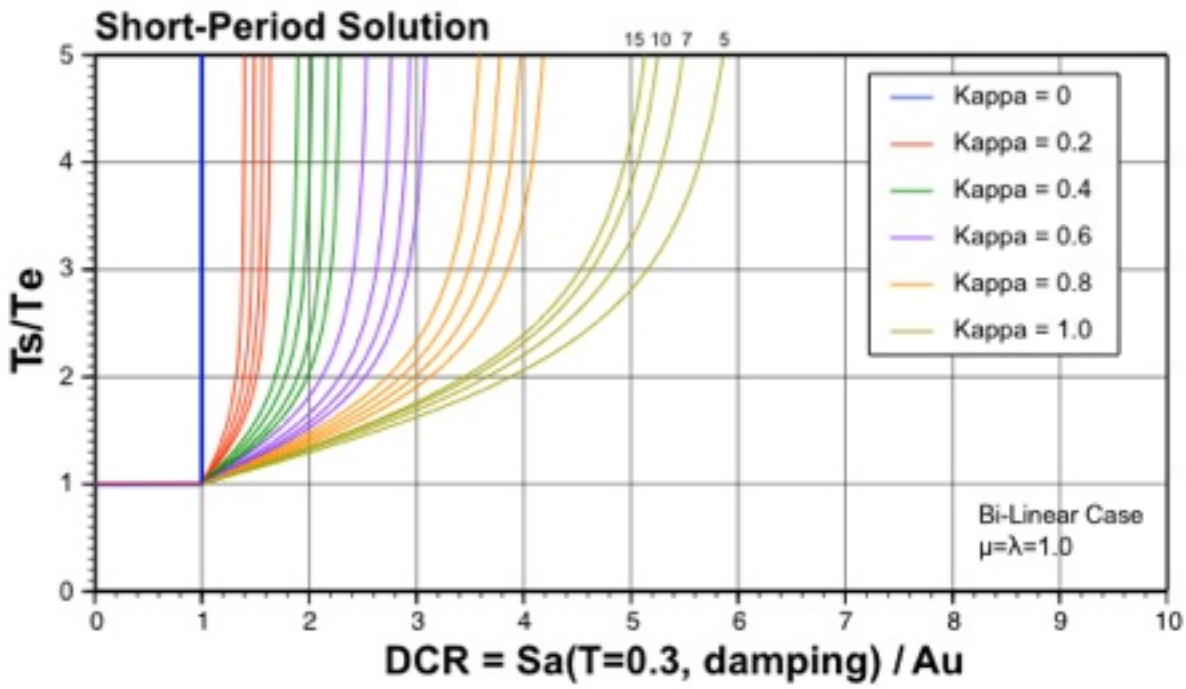

Figure 7: Short-Period Solution for Bi-Linear Capacity Curve

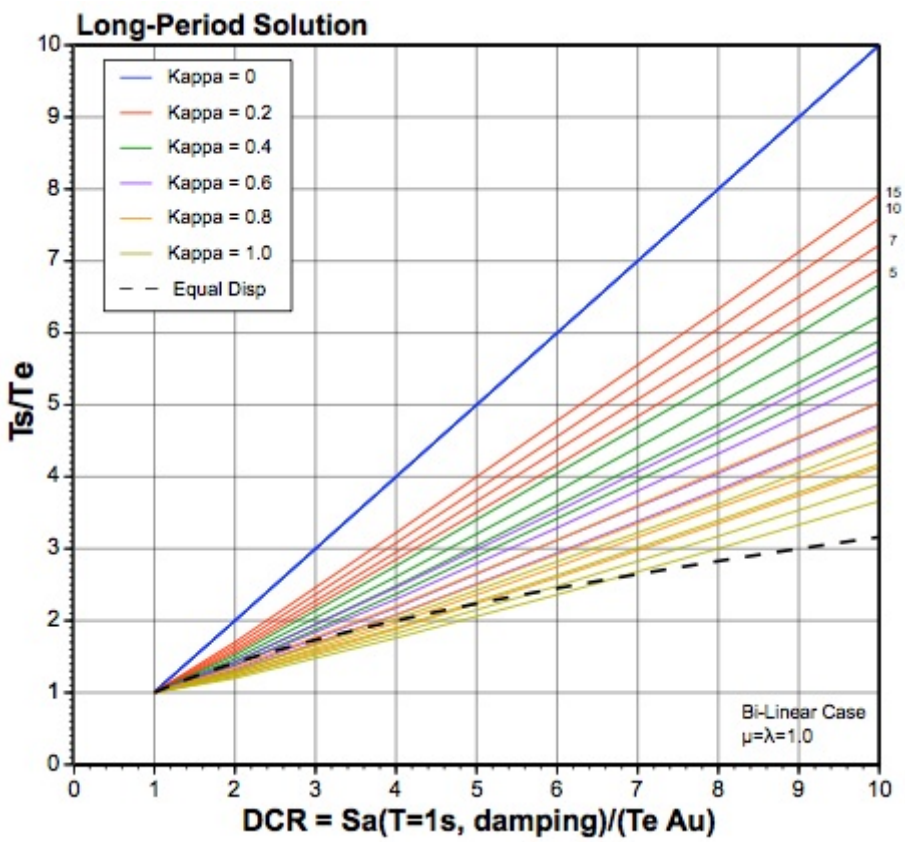

Figure 8: Long-Period Solution for Bi-Linear Capacity Curve

"Equal-Displacements Rule"

Under some conditions (specifically, with high Kappa values, for solutions in the velocity-controlled part of the ground motion spectrum) theoretically correct Capacity-Spectrum solutions can violate the "equal-displacements rule," which implies that (all other factors being equal) increasing the strength of the SDOF oscillator results in equal or smaller oscillator displacements. Without the imposition of the Equal-Displacements Rule, increasing the strength of a building (without change to stiffness, Kappa or other factors) can actually result in increased structural damage, contrary to accepted structural engineering logic.

The "Equal Displacements Rule" has been shown by many nonlinear dynamic procedure (NDP) studies of SDOF systems to provide a lower bound for inelastic response. A constraint is needed to represent the "Equal Displacements Rule" within the general HAZUS solution space for Capacity Spectrum Method.

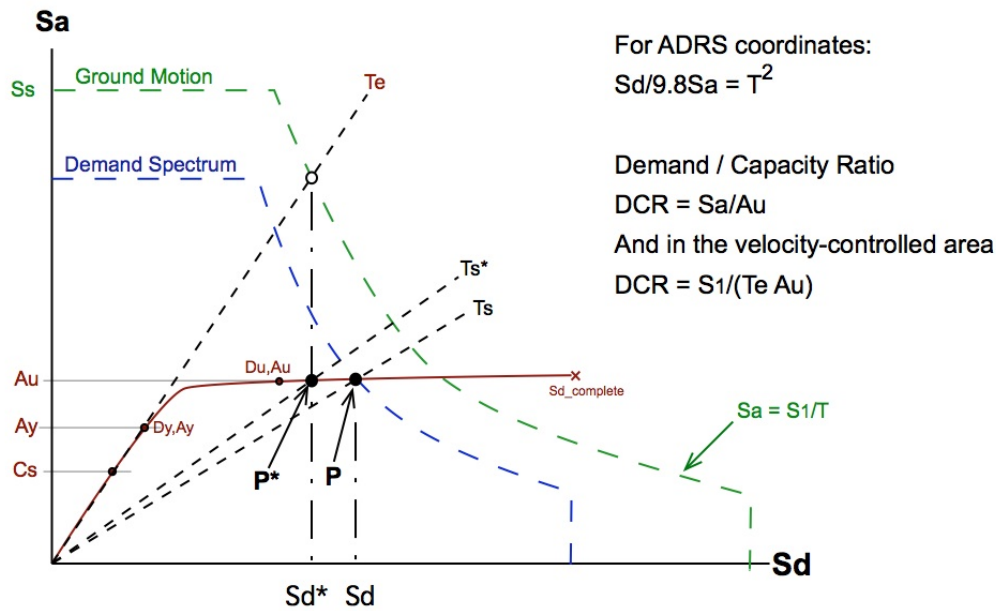

Figure 9: Capacity Spectrum and 'Equal Displacements'

Referring to Figure 10, let:

Te = elastic period

Ts = solution period @ performance point (Sa, Sd)

Ts* = solution period @ displacement of elastic oscillator with period Te

'Equal Displacements' would require Sd ≥ Sd* and consequently Ts ≥ Ts*

Examine Special Case: Sd and Sd* ≥ Du, so the performance point is found on the flat part of the Capacity Curve

$Te^2 = Te\ Sd^*/(9.8\ S1)$

$Te = Sd^*/(9.8\ S1)$ so $Sd^* = 9.8\ S1\ Te$

$(Ts^*)^2 = Sd^* / 9.8Au$ substitute for Sd* to obtain $(Ts^*)^2 = S1\ Te/Au$

$(Ts^*/Te)^2 = S1 / (Te\ Au) = DCR$ so $Ts^*/Te = SQRT(DCR)$

Figure 10 superimposes the equal displacement constraint to the general HAZUS solution space. Solutions below the line violate the "equal displacements" rule, and so are generally inadmissible.

Note on general case: In the transition from elastic to full plastic [i.e., from (Dy,Ay) to (Du,Au)], the expression for the constraint becomes more complex. In these cases, Ts* occurs on the Capacity Curve ellipse at Sd* = 9.8 S1 Te.

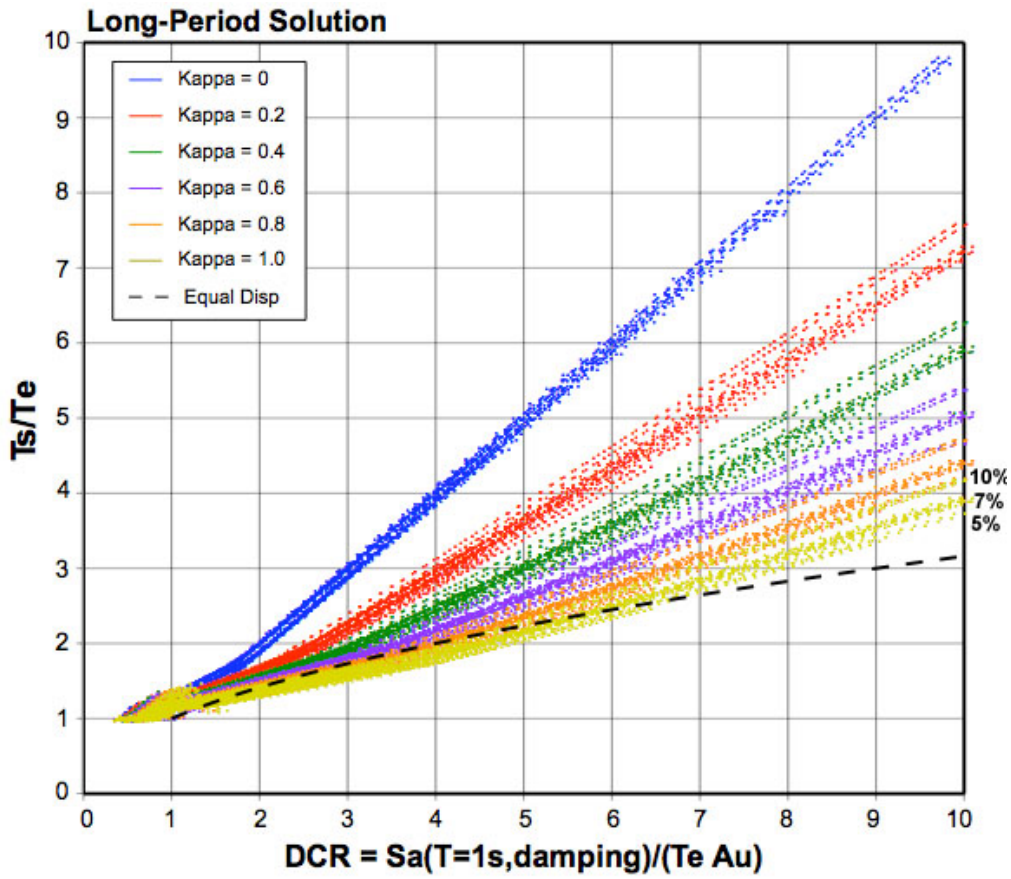

Figure 10: Effect of "Equal-Displacements" Constraint on Solution Space

As implemented for BCA, the software checks for violations of the "equal displacements rule," and imposes a displacement equal to the displacement of an identical oscillator (except with infinite strength) when violations are detects. In this way, an increase in the strength of the lateral force resisting system will not result in an increase in damage to the structural drift-sensitive system.

Using the System to Estimate Damage for Particular Buildings

For structural retrofit, the user of the BCA Structural Full Data Module is assumed to have the direct assistance of a Professional Engineer (Civil or Structural) who is experienced in the design of buildings to resist seismic loadings in accordance with current design codes (e.g., IBC 2006) and seismic rehabilitation guidelines (i.e., ASCE 31-03; ASCE 41-06; FEMA 547/2006 Edition).

The basic input parameters for the BCA damage model are familiar to engineers, and guidelines exist (e.g., ASCE 31-03) to guide the user faced with archaic building systems and materials. The Engineer assesses the existing design and construction, and prepares a retrofit design. The Engineer assigns the Model Type corresponding to the building gravity system and lateral force-resisting system, and specifies the height (number of stories). The Engineer assigns the assigns a "design level" before and after retrofit, and the software will provide HAZUS default parameters for estimates of all of the needed HAZUS parameters (Te, Cs, γ, λ, μ, κ, $\alpha 1$, $\alpha 2$ and elastic damping). The Engineer then modifies the elastic period (Te), and lateral strength (Cs), and to better represent the specific building in question before and after retrofit. The knowledgeable user may also wish to modify Kappa (κ) and the acceleration and drift damage thresholds to better represent the building systems pre- and post-retrofit.

When applied to individual buildings, the engineering analysis should go beyond mere classification of the structural system and code-type calculations of period and minimum required design base shear. The HAZUS damage relationships, and hence the relationships presented herein, presume that a complete, designed lateral force-resisting system is present, and that the building is regular in plan and in height. Calculations may be needed to ensure that appropriate model parameters are used, and to adjust the results to account for irregularity. In addition to using a tool like ASCE 31-03 to evaluate the gravity and lateral system, the Engineer must assess the current condition of the building and quality of construction, and consider:

- What irregularities exist, and were appropriate and adequate measures used in design to avoid increased damage from these irregularities?
- Does the lateral force-resisting system possess adequate redundancy? Structures with low redundancy can experience high levels of damage from failure of a few critical components. This implies higher average damage and higher damage variance.
- Was this building constructed in an area where earthquake design and construction is common? For buildings to perform well in earthquakes, a complete "infrastructure" for quality must exist: good workmanship with good materials, good design standards, good design, inspection and enforcement. Where any of these elements are lacking, poor structural performance may result.

Setting HAZUS Parameters to Represent Pre- & Post-retrofit Conditions in the BCA Tools

A number of user-modifiable parameters are provided in the BCA tools to allow the user to adjust structural and nonstructural vulnerability to represent the subject building before and after retrofit. The evaluation of the building, the selection of seismic retrofit techniques, and the modeling the building's vulnerability in its pre- and post-retrofit condition should be done under the direction of an experienced Professional Engineer (Civil or Structural).

To provide the appropriate parameters for accurate benefit-cost analysis, it is important to understand the HAZUS framework. HAZUS uses the Capacity Spectrum Method (CSM) as presented in ATC-40. The Capacity Spectrum Method which depicts earthquake demand and structural capacity within the acceleration-displacement response spectrum (ADRS) format – spectral acceleration (Sa) vs. spectral displacement (Sd) [Freeman, 11ECEE, 1998]. The ground motion spectrum is transformed into a demand spectrum, accounting for structural damping and hysteretic energy dissipation. The force-displacement behavior of the building is depicted within this framework by a 'capacity curve' as shown below. The HAZUS-MH Technical Manual, ASCE 41-06 and ATC-40 Chapter 8 describe how a nonlinear static procedure can be used to compute a pushover curve, which may then be translated into the ADRS format as a capacity curve. For the present purpose, it is sufficient to know that in the Capacity Spectrum Method, the building's earthquake response is idealized by a single-degree-of-freedom oscillator. Sd represents the lateral displacement of the oscillator, and Sa represents the lateral force per unit of seismic mass. Radial lines from the origin represent periods of oscillation.

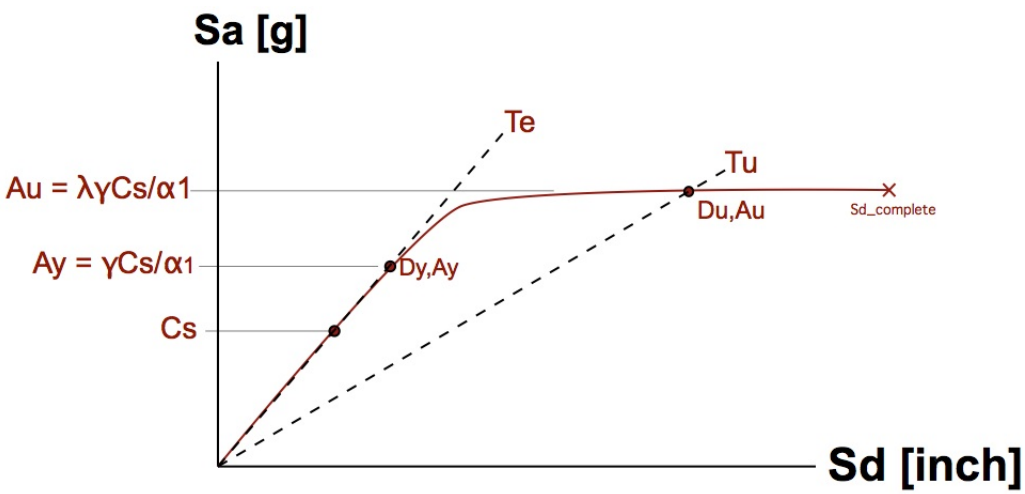

Figure 11 – HAZUS Parameters

Te – fundamental period of the structure in its elastic response, in (seconds)

Cs – design-level base shear, in terms of load-and-resistance-factor design (LRFD)

α1 – the fraction of building weight effective in the pushover mode,

α2 – the fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement (not shown in Figure 11),

γ – an "overstrength" factor relating "true" yield strength to design strength,

λ – an "overstrength" factor relating ultimate strength to yield strength, and

μ – a "ductility" ratio relating displacement at full plastification to lamda times the yield displacement (i.e., assumed point of significant yielding of the structure).

Overview – User Input for Structural Full Data Module

When the user selects a Model Building Type, Height, and Design Level to represent the pre-retrofit condition or the post-retrofit condition, it allows the software to pre-set various parameters to be generally consistent with typical buildings of the same class and design level. The user may then adjust the key parameters (Cs, Te, Kappa and Damage State Medians) to best represent the particular building in its pre-retrofit and post-retrofit condition.

Model Building Type

HAZUS provides the following basic building types.

MODEL BLDG TYPE	DESCRIPTION
W1	Wood, Light Frame (less than 5,000 sq. ft.)
W2	Wood, Greater than 5,000 sq.ft.
S1	Steel Moment Frame
S2	Steel Braced Frame
S3	Steel Light Frame
S4	Steel Frame with Cast-In Place Concrete Shear Walls
S5	Steel Frame with URM Infill Shear Walls
C1	Concrete Moment Frame
C2	Concrete Shear Walls
C3	Concrete Frame with URM Infill Shear Walls
PC1	Pre-cast Concrete Tilt-Up Walls
PC2	Precast Concrete Frames with Concrete Shear Walls
RM1	Reinforced-masonry Bearing Walls with Wood or Metal Deck Diaphragms
RM2	Reinforced-masonry Bearing Walls with Precast Concrete Diaphragms
URM	Unreinforced Masonry Bearing Walls
MH	Manufactured Housing

HAZUS does not specifically address reinforced-masonry bearing wall buildings with cast-in-place concrete diaphragms. These may be assigned to RM2 – Reinforced-masonry Bearing Walls with Precast Concrete Diaphragms.

HAZUS does not distinguish between eccentric braced steel frames and concentric braced steel frames. Eccentric braced steel frames may permit greater drifts before complete structural damage. Eccentric

braced steel frames may have longer structural periods. Well detailed eccentric braced steel frames may permit use of higher Kappa values.

HAZUS does not specifically address buckling restrained brace systems or supplemental dampers.

Buckling restrained bracing system may be approximated by revising Te and Cs, and using Kappa = 1.

The effect of supplemental dampers in seismic rehabilitation may be approximated by increasing the elastic damping in the post-retrofit system. The software allows users to assign structural damping of up to 15% of critical damping.

HAZUS does not address base isolation.

Height

[In number of stories]. The user should input the actual number of stories above the seismic base (i.e., grade). The software will then assign default HAZUS parameters for low-rise (1-3 stories), mid-rise (4-7 stories), or high-rise (8+ stories) where appropriate.

Design Level

This is a descriptor used in HAZUS to classify the degree of seismic resistance of a structural system as a function of its strength and detailing, relating to the seismic code under which it was designed, the local seismic zone, the design and construction practice of the era. For the present purpose, we simplify and generalize as follows:

High Code: UBC jurisdictions, Zones 3 & 4, Post-1976
also – ICSSC RP 6 [2002] "Benchmark Buildings"

Moderate Code: UBC jurisdictions, Zone 3 (highest), Pre-1976

Low Code: UBC Seismic Zone 2 or other areas where some (minimal) seismic design requirements were enforced at the time of original construction.

Pre-Code: Any location where building design and construction pre-dates the effective enforcement of seismic design codes.

Fundamental Elastic Structural Period, Te

Te is the fundamental period of the structure in its elastic response, in (seconds). The structure's fundamental period is used to estimate the maximum force that an earthquake may demand from the structure, if the structure were to remain elastic. That is, *Te* affects the 'force demand' upon the structure.

The fundamental elastic period of a building structure may be estimated in many

ways:

- from period equations in building codes,
- analysis, using structural engineering analysis software (e.g., ETAPS, SAP, Perform3D, RISA, STAAD, etc.), or by manual calculation,
- by measurement (pre-retrofit) using seismic instrumentation

Note that formulas in seismic building codes tend to provide a lower bound of fundamental elastic period of a building structure. The formulas are intended to underestimate the period and thereby increase design forces for mid- and high-rise structures.

Most structural retrofit methods (adding shear walls or bracing, reinforcing frames, etc.) will reduce the structure's fundamental elastic period. *Te* must be estimated for the pre-retrofit condition and the post-retrofit condition, and input in the fields provided.

Design Strength, Cs

Cs is the design-level base shear coefficient, representing the actual lateral strength of the building, at load-and-resistance-factor design (LRFD) level. Cs is expressed as a fraction of the building's seismic weight (i.e., V = Cs W). In HAZUS, this base shear is scaled up by an overstrength factor *(Gamma, γ)* to estimate the lateral force level at first significant yielding. The yield strength is then scaled up by another overstrength factor *(Lamda, λ)* to go from initial yield to the full plastic capacity, *Au.*

Most structural retrofit methods (adding shear walls or bracing, reinforcing frames, etc.) will increase the structure's lateral strength. Cs must be estimated for the pre-retrofit condition and the post-retrofit condition, and input in the fields provided.

The design-level base shear coefficient of an existing building structure may be estimated in many ways:

- from lateral force equations in building codes used in the original building design, or
- analysis, using structural engineering analysis software (e.g., ETAPS, SAP, Perform3D, RISA, STAAD, etc.), or by manual calculation.

Note that in codes that give lateral design forces in Allowable Stress Design (e.g., the Uniform Building Code prior to 1994), the lateral force coefficient should be multiplied by 1.4 to convert to load-and-resistance-factor design (LRFD) level.

The design-level base shear coefficient of the building structure following retrofit should be estimated by the Civil or Structural Engineer serving as the retrofit design Engineer-of-Record.

Alternatively, the design-level base shear coefficient of the building structure following retrofit may be specified by rehabilitation design standards or by project design specifications.

Ductility Factor, μ

μ (Mu) is a HAZUS parameter, introduced with the idealization of the Capacity Curve from the Capacity Spectrum Method. As such, it is not discussed in ATC-40 or other foundational documents. μ is a "ductility" ratio relating displacement at full plastification to lambda times the yield displacement (i.e., assumed point of significant yielding of the structure).

$$\mu = Du/(\lambda Dy)$$

So in HAZUS, μ is a measure of the <u>system</u> ductility in transition from yield to a fully developed plastic state. Note that this is <u>not</u> the same as the conventional definition of ductility ratio (μ) which is found as the building or element deformation, divided by the deformation at yield. Ductile capacity ratios are then found as building or element deformation at failure, divided by the deformation at yield. [Surprisingly, in HAZUS, damage states for the structural drift-sensitive system are not defined using conventional ductile capacity ratios, but are rather set according to absolute drift ratios for each design level.]

It may be difficult for the users of the BCA tools to set the μ parameter effectively. For this reason, we developed a method related to seismic design level and height, as follows.

In California, older hospital buildings that have been designated as unsafe for long-term acute-care usage are being evaluated using HAZUS, to see whether some may be spared the expense and cost of structural retrofit. The regulatory agency for hospitals in California (the Office of Statewide Healthcare Planning and Development, or OSHPD) published guidelines for HAZUS usage in this application. [OSHPD, 2007] gives the HAZUS μ factor as a function of number of stories, for buildings 1-15 stories in height (see below). The OSHPD table (A6-6) appears to follow values shown in the HAZUS Technical Manual (Table 5-6) for 'moderate code' design level. The relations used by OSHPD are modified to suit the present purpose, adding a curve for 'high code' and 'low and pre-code.'

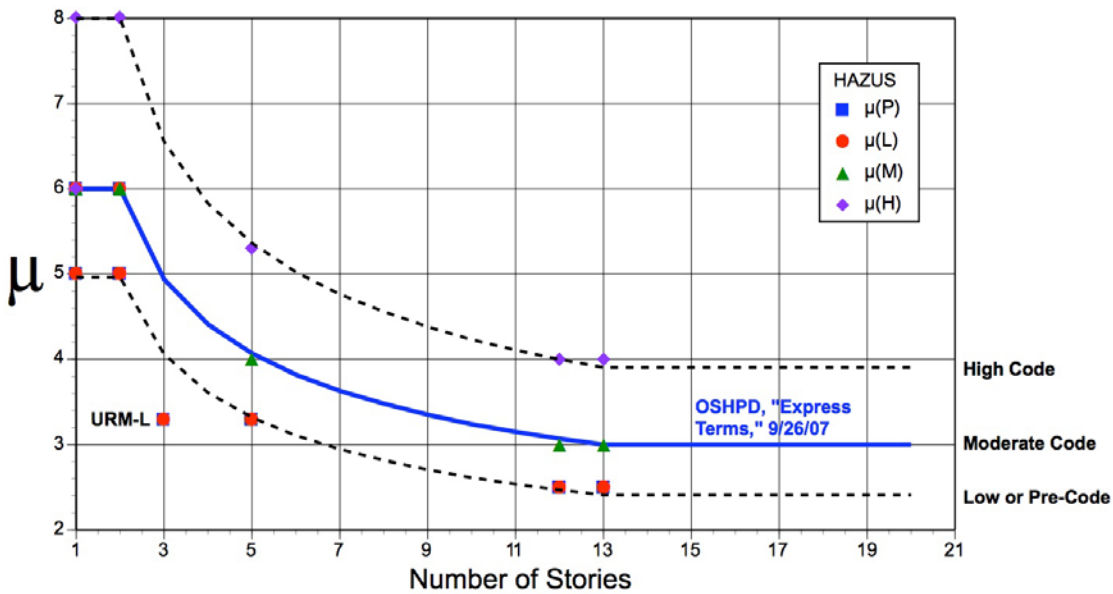

Figure 12 – μ Factor as a function of height and Design Level

Hysteretic Degradation Factor, Kappa, K

Kappa is the degradation factor, describing the fraction of the area of full hysteretic loops that remains at the end of the earthquake response. Kappa refers to the principal lateral force resisting elements and their detailing for stiffness and ductility. Kappa has a major impact on period lengthening and drift, and hence a major impact on HAZUS damage estimates. The Kappa (κ)factor must be estimated for the pre-retrofit condition and the post-retrofit condition, and input in the fields provided.

ATC-40, Chapter 8 discusses the Kappa factor, (κ) referred to as the (hysteretic) "Damping Modification Factor." Kappa ranges from zero to 1.0. It is a system parameter representing the principal lateral force resisting elements and their detailing for stiffness and ductility. For perfect, nondegrading systems, Kappa = 1.0. For severely pinched and degrading systems, Kappa = 0.0.

In ATC-40, for stiffness degrading reinforced concrete structures, Kappa ≥ 0.52, and for stiffness and strength degrading reinforced concrete structures, Kappa ≥ 0.33.

Chapter 5 of the HAZUS-MH Technical Manual, Section 5.6.2.1 discusses the Kappa factor, calling it a "degradation factor" that "defines the effective amount of hysteretic damping as a function of earthquake duration." The values used in HAZUS are listed in Table 5.18 of the HAZUS-MH Technical Manual. The values are a function of the number of inelastic cycles that may be demanded of the lateral force resisting system, with long duration (high-magnitude)

earthquakes on nearby faults driving the structure into many inelastic cycles, and so causing maximum degradation.

One of the principal objectives of structural seismic rehabilitation is to improve the resistance of the structural system to the loss of strength and stiffness. Older non-retrofitted elements (i.e., pre-1976 reinforced concrete, or steel moment frames with complete-penetration welded girder-to-column connection designed before to the 1994 Northridge earthquake) may have very low Kappa values (0 to 0.3), especially in sustained strong ground shaking. The following table is offered for guidance.

Kappa Factors – Existing Buildings

			Pre-Benchmark		Post-Benchmark	
Building Model Type Description	Model Building Type	Benchmark Date	Near Large Active Fault	Not Near Large Active Fault	Near Large Active Fault	Not Near Large Active Fault
Wood, Light Frame (less than 5,000 sq. ft.)	W1	1980	0.2	0.4	0.4	0.6
Wood, Greater than 5,000 sq.ft.	W2	1980	0.2	0.4	0.4	0.6
Steel Moment Frame	S1	1995	0.3	0.5	0.7	0.9
Steel Braced Frame	S2	1993	0.2	0.4	0.4	0.5
Steel Light Frame	S3	1990	0.1	0.3	0.3	0.5
Steel Frame with Cast-In Place Concrete Shear Walls	S4	1990	0.2	0.4	0.4	0.5
Steel Frame with Unreinforced Masonry Infill Walls	S5	none	0.0	0.3	0.0	0.3
Concrete Moment Frame	C1	1980	0.1	0.4	0.4	0.8
Concrete Shear Walls	C2	1990	0.1	0.3	0.4	0.9
Concrete Frame with Unreinforced Masonry Infill Walls	C3	none	0.0	0.2	0.0	0.2
Pre-cast Concrete Tilt-Up Walls	PC1	1994	0.1	0.2	0.4	0.6
Precast Concrete Frames with Concrete Shear Walls	PC2	1990	0.1	0.3	0.3	0.7
Reinforced Masonry Bearing Walls–Flexible Diaphragms	RM1	1994	0.1	0.2	0.4	0.6
Reinforced Masonry Bearing Walls–Rigid Diaphragms	RM2	1990	0.1	0.3	0.4	0.9
Unreinforced Masonry Bearing Walls	URM	none	0.0	0.3	0.0	0.3
Manufactured Housing -- bolted to concrete foundation	MH	none	0.2	0.4	0.4	0.6
Manufactured Housing -- on jacks or stands	MH	none	0.0	0.0	0.0	0.0

Added elements (e.g., shear walls) designed to current code may achieve high Kappa values (typically in the range of from 0.7 to 1.0).

Other Factors

In addition to the above, a number of other parameters also affect damage in HAZUS.

Median Thresholds for Complete Damage States

STR_Complete, NSD_Complete, NSA_Complete

HAZUS uses the estimated drift and acceleration response to an input ground motion spectrum to compute the probability that the building will be in a number of defined damage states (i.e., none, slight, moderate, extensive, and complete). The damage state probabilities are used to compute a weighted-average or expected (mean) repair cost.

$DF = \sum[P(i) \times DF(i)]$ for i=1,5

i = 1 (none), 2 (slight), 3 (moderate), 4 (extensive), and 5 (complete)

P(i) = probability of being in damage state (i)

DF(i) = cost to repair from damage state (i), divided by replacement value

Separate thresholds are set for drift-sensitive structural elements, for drift-sensitive nonstructural elements, and for acceleration-sensitive nonstructural elements. In the BCA software, the user can re-set the median drift values for the threshold of the complete damage state, and the thresholds for other damage state are scaled accordingly.

STR_Complete

STR_Complete is the displacement threshold for the complete damage state for Structural Drift Sensitive elements.

Seismic rehabilitation of structural elements may increase the ability of the vertical elements (i.e., walls, columns, or braces) in the structural system to sustain lateral deformation (drift) without damage, or to reduce the damage sustained by these structural elements from drift. If all of the vertical structural elements are rehabilitated to increase their lateral deformation capacity, the structural drift threshold for the whole building may be re-set accordingly. Where walls or bracing are added, but the lateral deformation capacity of other vertical elements are not improved by the selected retrofit, then the median drift threshold for complete damage should remain the same in the pre- and post-retrofit analysis.

NSD_Complete

NSD_Complete is the displacement threshold for the complete damage state for Nonstructural Drift Sensitive elements.

Seismic rehabilitation of nonstructural elements may increase the ability of the vertical elements (i.e., cladding, partition walls) in the nonstructural system to sustain lateral deformation (drift) without damage, or to reduce the damage sustained by these structural elements from drift. If all of the vertical nonstructural elements are rehabilitated to increase their lateral deformation capacity, the drift threshold for the whole building may be re-set accordingly. Where the deformation capacity of pnly selected vertical elements is improved, then the median drift threshold for complete damage for the affected elements can be se-set, and the median drift threshold for complete damage for the unaffected elements should remain the same in the pre- and post-retrofit analysis. The BCA software allows the user to specify the affected components, the fraction of overall value of the nonstructural drift-sensitive elements represented by the affected components, and the new drift threshold for complete damage.

NSA_Complete

NSA_Complete is the average floor acceleration at which complete damage occur to acceleration-sensitive nonstructural elements.

Seismic rehabilitation of acceleration-sensitive nonstructural elements (suspended ceilings, building service equipment, etc.) may increase their ability to sustain lateral accelerations without damage, or to reduce the damage sustained by these nonstructural elements from acceleration. If all of the acceleration-sensitive nonstructural elements are rehabilitated to

increase their lateral acceleration capacity, the acceleration damage threshold for the whole building may be re-set accordingly. Where the acceleration capacity of only selected nonstructural elements is improved, then the median acceleration threshold for complete damage for the affected elements can be se-set, and the median acceleration threshold for complete damage for the unaffected elements should remain the same in the pre- and post-retrofit analysis. The BCA software allows the user to specify the affected components, the fraction of overall value of the nonstructural acceleration-sensitive elements represented by the affected components, and the new acceleration threshold for complete damage. The software also allows the user to designate affected items as 'mounted at or below grade' or 'mounted above grade,' so that appropriate equipment mounting point accelerations are applied.

FRAC

The fraction of value of the acceleration-sensitive nonstructural components found at or below grade. The remaining acceleration-sensitive nonstructural components are assumed to be mounted above grade, and subject to building floor motions. FRAC may be re-set by the user to more precisely represent the actual conditions in the building.

Elastic Damping (%)

HAZUS uses the following damping levels for structural damping:

MODEL BLDG TYPE	DESCRIPTION	**Structural Damping**
W1	Wood, Light Frame (less than 5,000 sq. ft.)	15
W2	Wood, Greater than 5,000 sq. ft.	10
S1, S2	Steel (Moment Frame or Braced Frame)	5
S3	Steel Light Frame	7
S4	Steel Frame with Cast-In Place Concrete Shear Walls	7
S5, C3	Steel or Concrete Frame with URM Infill Shear Walls	10
C1, C2	Concrete (Moment Frame or Shear Wall)	7
PC1	Pre-cast Concrete Tilt-Up Walls	7
PC2	Precast Concrete Frames with Concrete Shear Walls	7
RM1	Reinforced-masonry Bearing Walls with Wood or Metal Deck Diaphragms	10
RM2	Reinforced-masonry Bearing Walls with Concrete Diaphragms	7
URM	Unreinforced Masonry Bearing Walls	10
MH	Manufactured Housing	5

Dependence of Nonstructural Damage on the Structural Complete Damage State

The expert panel for this project included Dr. Jawhar Bouabid of RMS. In conversations with Dr. Bouabid, one of the creators of the HAZUS program, he pointed out to URS that the nonstructural damage states are independent on the structural damage state, except when the structure is in the "complete" damage state. The structure does not have to be in the "collapsed" damage state, but when structural damage is complete, the structure is likely to be demolished, with no salvage of nonstructural drift- or acceleration-sensitive components.

We note that this is in contradiction to the current HAZUS-MH Technical Manual: "The Methodology assumes nonstructural damage states to be independent of structural damage states" (Ch. 5, section 5.6.2.2, HAZUS-MH MR3 Technical Manual), but Dr. Bouabid assured URS that this feature is implemented in the HAZUS software.

When the structural system (STR) is in the Complete damage state, it is assumed that the non-structural drift-sensitive (NSD) and non-structural acceleration-sensitive (NSA) components are in the Complete damage state as well. The following probability calculation shows how this damage state dependence is considered in this implementation for FEMA.

Assume the probability that the STR is in the Complete damage state is P_{c-STR}, then the probability that the STR is in the non-Complete damage state is (1 – P_{c-STR}). Assume that the probability of the NSD or NSA components in a particular damage state is P_{ds} (*ds* =1, 5, for the None, Slight, Moderate, Extensive and Complete, respectively), as defined in the HAZUS manual. Therefore,

When STR is in non-Complete damage state, the adjusted probability $P_{ds}^{'}$ is:

$P_{ds}^{'}$ = (1 – P_{c-STR}) * P_{ds}, ds = 1, 5

Similarly, when STR in Complete damage state:

$P_5^{'}$ = P_{c-STR} * 1.0, ds = 5

Adjusted damage state probability:

P_{ds} * = (1 – P_{c-STR}) * P_{ds}, ds = 1, 4
P_5 * = (1 – P_{c-STR}) * P_5 + P_{c-STR}

The total adjusted accumulative probability is:

$$\sum_{ds=1}^{5} P_{ds}* = P_{ds}^{'} + P_5^{'} = (1 - P_{c-STR})\sum_{ds=1}^{5} P_{ds} + P_5^{'} = (1 - P_{c-STR}) + P_{c-STR} = 1$$

Role of the Expert Panel

URS retained an expert panel in the adaptation of HAZUS for earthquake benefit-cost analysis. The panel included Dr. Farzad Naeim, Esq., of John A. Martin Assoc., Dr. Keith Porter of University of Colorado, and Dr. Jawhar Bouabid of RMS. Dr. Bouabid was one of the creators of the HAZUS program. Dr. Porter has done extensive work with HAZUS, and is an originator of the Assembly-Based Vulnerability methodology, also used to generate vulnerability relationships. Dr. Naeim was the editor of EERI's Spectra Journal, is experienced with HAZUS, and served as the chairman of the panel.

Other members of the panel included senior URS staff:

Mike Mehrain, Ph.D., S.E.
Allan Porush, ECE, S.E.
Mark R. Gorman, Ph.D., C.E
Craig Parent, P.E., principal investigator, BCAR Nonstructural Module

Two FEMA representatives participated in the first Expert Panel meeting in Los Angeles:

Gina White, Mitigation Branch Director, FEMA JFO Pasadena
Clayton Pang, Architect, FEMA

The panel met in Los Angeles to review work by the principal investigators (W. Graf, C.E., and Y.J. Lee of URS in Los Angeles) the recommended methodology and approach, and to make recommendations for the implementation. Additional meeting were held by telephone, and URS project members met with Dr. Naeim in his Los Angeles office to test the implementing software and provide feedback.

Limitations of the Model

Damage from Ground Shaking Only

The models adapted from HAZUS in this application address only damage from strong ground shaking. Damage from slope failures, foundation failures, liquefaction effects, surface fault rupture, etc. are not addressed by these models, and in general require detailed, site-specific investigation by geotechnical professionals working with the Professional Engineer.

P-∂ Effects

HAZUS does not address P-∂ effects, but those are large at drift ratios associated with the 'complete' damage state in HAZUS.

Higher Modes

HAZUS, in its use of Capacity Spectrum Method, idealizes the building structure as a nonlinear single-degree-of-freedom oscillator. For this reason, HAZUS does not address multi-modal effects (e.g., buildings with a different framing system in the longitudinal and transverse directions, and "higher modes").

Conclusions

In the Benefit-Cost Analysis Reengineering (BCAR) effort for the seismic/structural module, URS developed a framework for the examination of earthquake damage cost as a function of the engineering parameters used in seismic design codes – ground shaking spectral acceleration, design base shear, fundamental period, height, and framing system. HAZUS as the source for the building damage models. This model provide an easy-to-use, flexible system to predict earthquake damage repair costs to buildings of all vintages, retrofitted buildings, etc., in a wide variety of seismic environments.

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