Estimating the Non-Structural Seismic Vulnerability of Building Categories

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SUMMARY:

Nonstructural components represent the majority of building construction cost and of earthquake repair costs. We propose an analytical method to derive seismic vulnerability functions for non-structural components in building categories, through a simplification of a state-of-the-art analytical method developed for the Pacific Earthquake Engineering Research (PEER) Center and codified in the ATC-58 guidelines. The simplification begins by designing one or more index buildings to represent the building category. One specifies building height, floor area, structural system, and the floor-by-floor quantity of the most-costly 5 or so nonstructural components. The analyst quantifies the story-level vulnerability of these components using the ATC-58 (or other) fragility and consequence functions. These are summed over the building height by structural analysis or using one of three standard mode shapes and a standard loading condition. The methodology is offered as part of the GEM Vulnerability Consortium's global vulnerability guidelines.

Keywords: Nonstructural components, fragility functions, vulnerability functions

1. INTRODUCTION

This paper presents a methodology developed for the Global Earthquake Model for deriving vulnerability functions for non-structural components of building categories. By "building category" is meant a group of buildings with common features, especially material, lateral force-resisting system, occupancy and height. To be clear, the present study focuses on deriving whole-building nonstructural vulnerability functions for a building category by analytical means, in particular, by a simplified version of PBEE-2. An importance challenge though is how to define the building category, that is, to describe and quantify the nonstructural components in the building. Therefore, this study examines three approaches to doing so, and compares results of the three methods. It offers guidelines for determining the best method based on accuracy and applicability for each method especially once there is overlap of the results. The guidelines are clarified and are illustrated with examples in the next chapter. For the sake of simplicity and clearness, the methodology is divided in three main steps as follow;

1.1. Step 1: select index building and identify top non-structural components

The method relies on the concept of an index building, that is, a real or hypothetical building designed in some detail and intended to be somehow representative of a broader class. For convenience, index buildings can be defined by reference: the analyst picks the most-similar building model in RS Means' square-foot construction-cost manual or that of any other construction cost reference that considers occupancy, structural material and height, such as ONDAC in Chile (http://www.ondac.com/principal.htm) or the BCIS Comprehensive Building Price Book in the UK (BCIS 2012a).

Next, one determines the story-by-story quantity and construction cost of nonstructural components that have the largest contribution to non-structural construction cost. It is sufficient to quantify the 5 or so nonstructural component categories that contribute most to the construction cost (new) of the index building. These are referred to as the top nonstructural component categories. Components are categorized here by the NISTIR 6389 (NIST, 1999) extension to US National Institute of Standards and Technology UNIFORMAT II 5-character code (NIST, 1999). By "story-by-story quantity" is meant the quantity of each component on each story, measured in units most commonly used for construction cost estimation, such as linear feet of partition, square feet of suspended ceiling, and number of elevators.

1.2. Step 2: deriving component vulnerability functions

Next, one creates aggregated vulnerability functions for each non-structural component to relate story-level seismic excitation to repair cost per unit of the component. By "aggregated vulnerability function" is meant that the vulnerability function reflects uncertainty in the details of each component. By "details" is meant that, for any given component category such as gypsum wallboard partition, there are details of the configuration, installation condition, size, damage states or other characteristics that matter to seismic fragility, so there are subcategories of the component each with their own sets of fragility functions. These details are straightforward to represent when analyzing a particular building, but too detailed for a building category, so they are aggregated.

One can think of the "aggregated" nonstructural components discussed here as grouped by the UNIFORMAT II or slightly more-detailed NISTIR 6389 (NIST 1999) labeling system, which label each building component with a 5-character hierarchical code of the form X0000. At its most-detailed, this system differentiates building components between, say, C1011 = fixed partitions, C1012 = demountable partitions. But within one such category the seismic vulnerability can vary greatly, e.g., between gypsum wallboard partitions with full-height sheathing and fixed top plates, and gypsum wallboard partitions with partial-height sheathing. The ATC-58 project (ATC, 2012), and the present research, uses fragility functions at this latter level of detail, referring to them as detailed vulnerability functions, and aggregates to the coarser lever of NISTIR 6389 (NIST, 1999), referring to them as aggregated vulnerability functions.

The present work relies on existing databases of detailed nonstructural components' fragility functions, especially that of the ATC-58 project, though the analyst is free to derive new detailed component fragility functions or take them from other sources.

Below is the method of aggregating vulnerability functions for different damage states and different sizes or capacities of a non-structural component *h*;

$$E[C \mid S = s, H = h] = \sum_{i=1}^{N_i} \sum_{d=1}^{N_d} P[D = d_i \mid S = s] \cdot E[C \mid D_i = d] \cdot W_h(i) \qquad (1)$$

E[A | B]: expected value of the uncertain variable A given knowledge B

C: repair cost, here of the aggregated component category *h*, measured in units of currency

S: seismic excitation imposed on aggregated component category h (also referred to as the demand parameter); can be measured in terms of member force, member deformation, acceleration, or other measure

H: a variable that indexes aggregated component categories

h: a particular value of *H*, i.e., an index to a particular aggregated component category

i: an index to a detailed component category within the broad component category h

N_i: number of possible detailed component categories *i* within broad component category h

D_i: uncertain damage state of detailed component category i, an index

d: a particular value of D

N_d: number of possible damage states that detailed component category i can experience, in addition to the undamaged state

$W_h(i)$: Fraction of components in aggregated category h that are of detailed type i, Default is $\frac{1}{N_i}$ and must sum over N_i to 1.0.

$E[C\ |D_i = d]$: mean repair cost for a unit of detailed component category i that is in damage state d.

$$P[D_i = d\ |S = s] = \varphi\left(\frac{\ln\left(\frac{s}{\theta_{id}}\right)}{\beta_{id}}\right) - \varphi\left(\frac{\ln\left(\frac{s}{\theta_{id+1}}\right)}{\beta_{id+1}}\right) \qquad for\ 0 < d < N_d \tag{2}$$

$$P[D_i = d\ |S = s] = \varphi\left(\frac{\ln\left(\frac{s}{\theta_{id}}\right)}{\beta_{id}}\right) \qquad for\ d = N_d \tag{3}$$

The parameters θ and β can be taken from existing libraries of fragility functions, especially that of ATC-58 (2012) or Johnson et al. (1999) Appendix C. Or they can be derived from available sources using the procedures specified in Porter et al. (2007). The mean consequence functions $E[C|D_i = d]$ can likewise be taken from an existing library such as ATC-58 (2012), from locally appropriate repair-cost guidelines such as Xactimate (Xactware, 2012) or BCIS (2012b), or from available local construction-contracting expertise.

The last term of the above equation, $W_h(i)$ is the weighting item in which the probability of usage of the nonstructural component of the database is determined. One can imagine four methods to determine $W_h(i)$, as follows.

a) Primary-guess procedure:

The least expensive but perhaps also least controlled approach is for analyst to guess the values of $W_h(i)$. The guesses should be documented with an explanation that includes: the analyst's construction or design experience, years in practice, consideration of the construction type, regional economy and climate (if applicable), and if possible, observations of actual buildings in the building category of interest.

b) Information from local construction material store:

In each area or region, one reasonable source for determining the relative usage of specific nonstructural component sizes or capacities is local construction material stores. Weights $W_h(i)$ are taken from the relative amount or number of usage of a nonstructural component of each size or capacity sold recently. This information is available in the construction-materials department at the local store. By dividing the number or amount of the specific item size or capacity they have sold within a year by the total number or amount of the same nonstructural type but different sizes or capacities, one can calculate the probability of using of that specific item.

c) Expert panel:

An expert panel comprises a few experts from the relevant fields of the specific nonstructural component under consideration. The expert panel could consist of a designer engineer who is familiar with the specific nonstructural component category, a local building official, and a construction contractor. The panel members should get together in a same place, be offered a description of the nonstructural component under consideration, and asked to reach a consensus on a reasonable mix of detailed component types, i.e., reasonable quantities $W_h(i)$. The concept of nonstructural probability of usage and the question they need to answer should be clear for them at the beginning so they totally understand what the reason of the question is.

d) Construction drawings:

Another way to determine probability of usage for non-structural components is to refer to architectural and MEP (mechanical, electrical and plumbing) design drawings for existing sample buildings in the region under consideration. The drawings can help one calculate the number of different sizes or capacities for each type of component used in the sample buildings as well as the total number of the components type used. By dividing the number of each size by the total number of component of all sizes and capacities, one can determine the probability of usage of that size or capacity.

1.3 Step 3: deriving story-level nonstructural component vulnerability functions

To determine the average vulnerability of nonstructural components of an index building, one next aggregates vulnerability of non-structural components within each story of the building. For present purposes, and following the examples of HAZUS-MH (NIBS and FEMA, 2007) and ATC-58 (ATC, 2012), two demand parameters are recognized: story drift and floor acceleration. One separately sums vulnerability of drift-sensitive and acceleration-sensitive components. Below is the method of adding repair cost of components categories for both drift sensitive and floor acceleration sensitive non-structural components. For component sensitive to peak transit drift;

$$\mathrm{E}[C_{PTD,n} \mid S_{PTD} = s, M = m] = \frac{\sum_{h=1}^{N_{NH,PTD}} E[C \mid S_{PTD}=s, H=h]\cdot Q(h \mid M=m)}{F(m)} \tag{4}$$

Where:

$C_{PTD,n}$: (uncertain) repair cost of all drift-sensitive components on story *n*
M: a variable that indexes building models
m: a particular value of M, i.e., a particular index building
S_{PTD}: (uncertain) peak transit drift ratio
$N_{NH,PTD}$: Number of top components that are sensitive to drift
$Q(h \mid M = m)$: quantity of component of type $H=h$ in a single story of a building of model m
$F(m)$: fraction of total non-structural construction cost that is contributed by the top components considered here, for the index building m

For components sensitive to peak floor acceleration;

$$\mathrm{E}[C_{PFA,n} \mid S_{PFA,n} = s, M = m] = \frac{\sum_{h=1}^{N_{H,PFA}} E[C \mid S_{PFA,n}=s, H=h]\cdot Q(h \mid M=m)}{F(m)} \tag{5}$$

$C_{FPA,n}$: uncertain repair cost for all acceleration-sensitive components attached to the floor of story *n*
$S_{PFA,n}$: (uncertain) peak floor acceleration of the floor of story *n*

1.4. Step 4: building-level non-structural components vulnerability function

Finally, the repair costs of drift-sensitive and acceleration-sensitive components are added for the whole building, to find the total nonstructural repair cost as follows:

$$E[C \mid M = m, X = x] = \sum_{n=1}^{N_s+1} E\left[C_{PTD,n} \mid M = m, S_{PTD,n} = \varphi_m^{n}(X)\right] + E\left[C_{PFA,n} \mid M = m, S_{PFA,n} = \varphi_m^{Ns+n}(X)\right] \tag{6}$$

X: Uncertain shaking intensity, e.g., S_a(1.0 sec, 5%); the most-common being: X ∈ { PGA_{gm}, S_a(0.3 sec, 5%), S_a(1.0 sec, 5%), PGV_{gm}, *MMI*, *EMS*-98}

x: Particular value of X

$\varphi_m^j(X)$: component j of the structural response for a building of model m, given X

N_S: Number of stories

1.3.1 Structural analysis and structural response vector, $\varphi_m(X)$

One needs to have a structural response vector $\varphi_m(X)$. Here, the vector need only contain peak transient drift ratio for each story and peak floor accelerations for each floor and the roof. It has $2N_s$+1 rows in which the first N_s are peak transient drift ratios and the remaining N_S+1 are peak absolute floor accelerations. The structural response vector has the following format;

$$\varphi_m(X) = \left[S_{PTD,1}(X), S_{PTD,2}(X), \ldots S_{PTD,N_s}(X), S_{PFA,1}(X), S_{PFA,2}(X) \ldots S_{PFA,N_s+1}(X)\right]^T \tag{7}$$

$S_{PTD,i}(X)$: Expected value of peak transit drift, story i, when building of model m is subjected to intensity X shaking

$S_{PFA,i}(X)$: Expected value of peak floor acceleration, floor i, when building of model m is subjected to intensity X shaking

Therefore, by finding the roof displacement and acceleration, one can determine lateral displacement of all stories and floor acceleration of the building or $\varphi_m(X)$vector. Ideally, the vector is the expected value of response produced by nonlinear dynamic structural analyses and varies nonlinearly with X. More simply, it might be the product of a nonlinear pseudostatic (pushover) structural analysis and vary nonlinearly with X. Or most simply, it could represent one of a few standard shapes and vary linearly with X. We do not discuss the structural analysis procedures the might be used in nonlinear dynamic or pseudostatic structural analyses.

Absent thorough nonlinear structural analysis, one could idealize the building's deflected shape as one of three cases: (1) for shearwall buildings, the deflected shape of an elastic cantilever beam with effectively infinite shear modulus and finite Young's modulus and moment of inertia, subjected to a distributed horizontal load that increases linearly with height per ASCE 7 (2010) Sec 13.3. (2) For frame buildings, the deflected shape of an elastic cantilever beam with finite shear modulus and cross-sectional area, and effectively infinite shear modulus, subjected to the ASCE 7 (2010) loading profile. (3) For dual systems or other intermediate cases, the deflected shape is taken as triangular, i.e., with constant peak transient drift ratio. The deflected mode shape in these 3 cases can be shown to be as follows, where w(x) denotes relative displacement at elevation x, in a building of height h:

$$\text{Shearwall: } \frac{w(x)}{w(h)} \approx \frac{x^2}{h^5}\frac{\left(70h^3 - 40h^2x + 5hx^2 + 2x^3\right)}{37} \tag{8}$$

$$\text{Frame: } \frac{w(x)}{w(h)} \approx \frac{x}{h^3}\cdot\frac{12h^2 - 3hx - 2x^2}{7} \tag{9}$$

$$\text{Dual system: } \frac{w(x)}{w(h)} \approx \frac{x}{h} \tag{10}$$

Roof absolute acceleration can be estimated assuming the building acts as a single-degree-of-freedom nonlinear oscillator with an elastic-perfectly-plastic pushover curve, using the N2 method proposed by Fajfar (1999). Its elastic period can be taken from the mean suggested by Chopra and Goel (2000) in the case of steel or concrete; from Camelo et al. (2001) in the case of timber; or from ASCE 7 (2010) or local guidelines where sources these do not apply. Its strength can be estimated from the unfactored design strength specified by local design requirements.

2. VALIDATION PROCEDURE

The results obtained from applying the methodology should be verified for their accuracy and acceptability. Several tests, not detailed here, can be used to check the results.

- ***Sanity check.*** In general, the results should satisfy experienced earthquake engineers regarding the total repair cost of non-structural components in a building given the detailed specifications and location of the building. If the results are too far from their opinion, the calculation should be rechecked.
- *Reasonable sensitivity to component quantities.* Results should vary if rooms and spaces in a building change. For example, bigger rooms should lead to a smaller total quantity of partitions and therefore to a smaller repair cost for partitions.
- ***Reasonable results relative to other buildings.*** The results can be compared with buildings with more-fragile or less-fragile non-structural components. The relative vulnerability functions should make sense: the building with less-fragile components should be lower (less loss for the same excitation) than the building with more-fragile components.
- ***Asymptotes to total loss.*** The total repair cost for high excitations should be close to 100%, i.e., near the total construction cost (new) such as that determined from construction costs manuals.

3. INDEX BUILDINGS AND SAMPLE CALCULATION

This section presents an illustration. Let us consider highrise residential reinforced concrete shearwall buildings. We use as our index building the RS Means (2007) model M.030, 8-24 story apartment building, illustrated in Figure 1.

Figure 1. Building model M.030, RS Means (2007)

We take the building as having 16 stories, roof height = 56m, 1500m^2/floor, total area 24,000m^2. The key non-structural components are listed below.

Table 1. Non-structural rank order contribution to total construction cost

RS Means model no.	Rank order contribution to total construction cost					Construction cost of top 5 components per sq. ft ($)	Total non-structural construction cost ($)	Fraction of total construction cost new	Fraction of total non-structural construction cost
	1	2	3	4	5				
M.030	Exterior walls	Elevators and lifts	Partitions	Plumbing fixtures	Cooling generating system	66.48	119.46	0.42	0.56

We next determine the aggregated vulnerability function for each of the above five components. Consider item 3, interior partitions. Per the cost manual and local expertise, the aggregated component type is C1010, gypsum wallboard partition, and the detailed type is ATC-58's C1011.001a, full-height gypsum wallboard partition on metal stud, fixed top and bottom. Figure 3 shows the aggregated vulnerability function for 100 lf of partition and the contribution to it from three damage states using Equation (1). The total quantity of partition on each floor is taken from RS Means (2007) Model M.030.

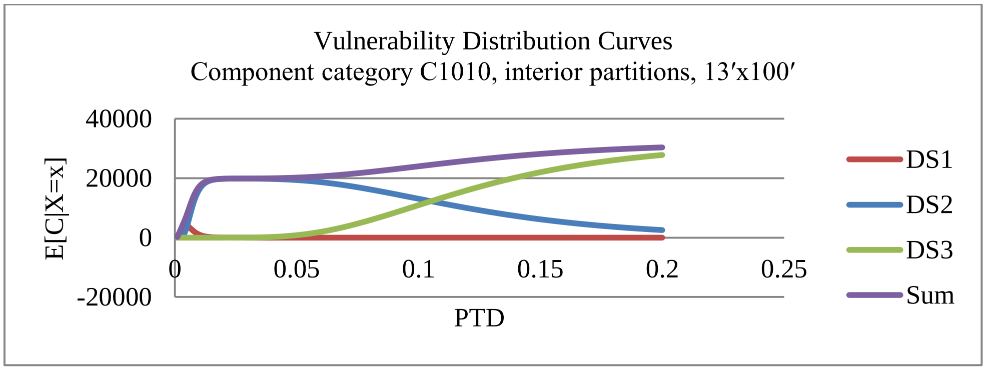

Figure 2. Component vulnerability function for 100 linear feet of interior partition.

Repeating the calculation for the other four top components and summing drift-sensitive and acceleration-sensitive component vulnerability functions per Equations (4) and (5) results in the story-level vulnerability functions illustrated below;

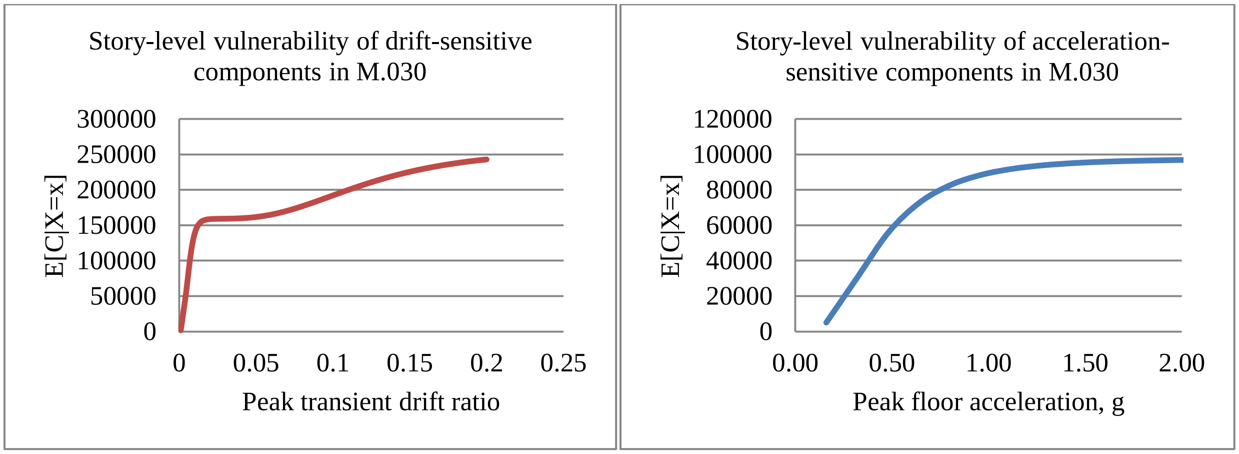

Figure 3. Left: Story-level vulnerability of drift-sensitive components in M.030. Right: Story-level vulnerability of acceleration-sensitive components in M.030

The total non-structural vulnerability function for the whole building is calculated by using Equation (6), the assumption of an idealized shearwall modeshape as specified in Equation (8), and the result is shown below;

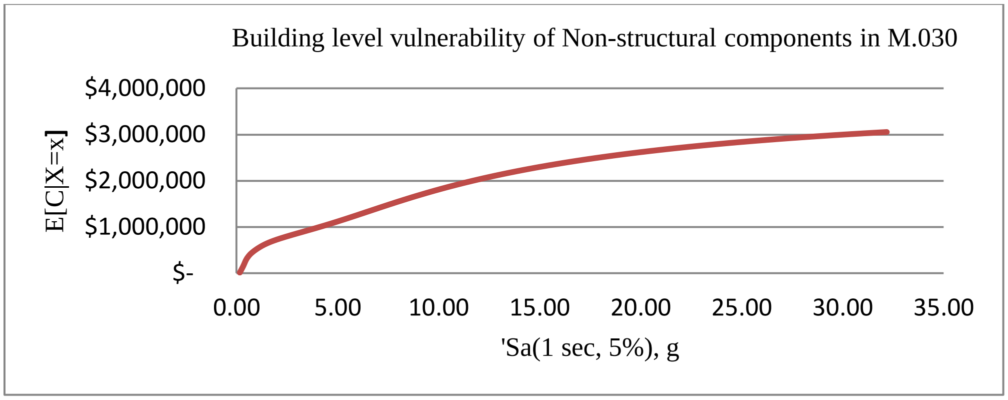

Figure 4. Building level vulnerability of Non-structural components in M.030

To test the methodology, we compared the vulnerability function derived above and comparable curves from HAZUS-MH (NIBS and FEMA 2009) and ATC-13 (Applied Technology Council, 1985). In particular, the HAZUS-MH-based vulnerability function is for highrise reinforced concrete shearwall, moderate code, multifamily residential occupancy ("C2H-m-RES3AF-DF"), as derived by Porter (2009). The ATC-13 vulnerability function is the one for highrise reinforced concrete shearwall with moment-resisting frame ("RC/SW-MRF/HR"). To make an apples-to-apples comparison, the nonstructural vulnerability function derived here is normalized by the whole-building construction cost new as estimated using RS Means (2007), and the HAZUS-MH vulnerability function for the structural part of the C2H-m-RES3AF-DF is added to the nonstructural part that is calculated here. As shown in the graph, reasonable agreement between the curves can be seen, and the derived curve looks reasonable.

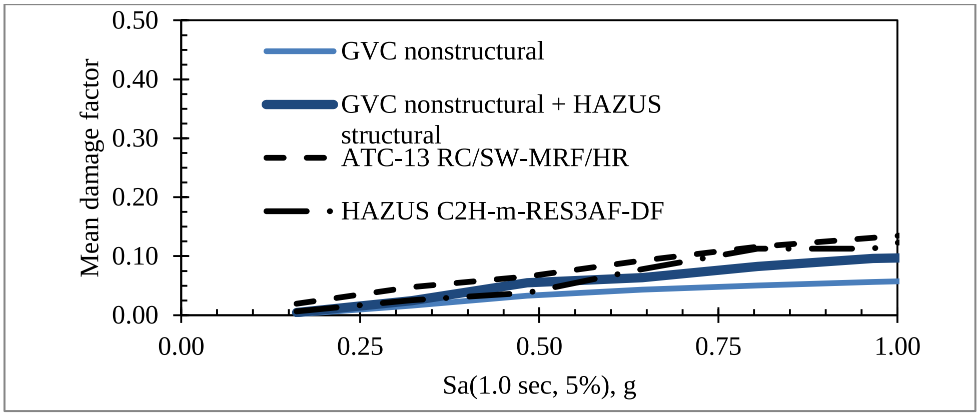

Figure 8. Comparison between the vulnerability function derived above and comparable curves from HAZUS-MH and ATC-13

4. UNCERTAINTY

We do not discuss treatment of uncertainty in detail here. Important sources include the variability in design within a broad category; the uncertainty in structural response for any index building given a particular level of IM; and uncertainty in repair cost given a specified damage state of a given component.

The first can be partially addressed by selecting multiple index buildings for each category. Note however that precedents exist for considering a single index building to represent an entire category. HAZUS-MH for example employs parameter values for a single representative example for each of its categories. The second source of uncertainty can be partially treated by employing multiple nonlinear dynamic analyses and by treating building period and strength as uncertain. Chopra and Goel (2000) for example provide evidence of the variability of building period for various structural systems. The third uncertainty can be treated as suggested by Porter (2010), by explicit calculation of the variance of repair cost conditioned on structural response. In the end though, all the required rigor might be prohibitively expensive and provide only illusory accuracy. In later work, we will recommend a function that provides a reasonable coefficient of variation of damage factor conditioned on mean damage factor, based on past detailed analyses of PBEE-2 models.

5. CONCLUSIONS

We offer an analytical procedure for estimating the mean nonstructural vulnerability of a building category. It requires one to select or design one or more index buildings to represent the category. The design is fairly schematic, requiring one to know the structural material, lateral force resisting system, height, floor area, the quantity of the top 5 or so nonstructural components that contribute most to the construction cost of the building, and the total nonstructural construction cost of the building. Each of these components is associated with a set of fragility functions and consequence functions from ATC-58 or others sources. Story-level vulnerability is calculated as a sum of the vulnerability of each component, and the building-level vulnerability is derived as a function of ground motion by adding story-level vulnerability accounting for mode shape, roof-level response, normalized by the fraction of nonstructural construction cost represented by the top 5 components.

The proposed methodology employs the same basic principles as the state-of-the-art methods specified in ATC-58, while reducing much of the effort. It draws on a substantial and growing body of fragility functions such as appear in the ATC-58 database, rigorously derived from laboratory tests or earthquake performance of fairly detailed building components. The consequence functions it uses are likewise drawn from the ATC-58 database or a variety of locally applicable repair-cost manuals and databases. At the same time, by focusing only on the top-5 nonstructural component categories, the analyst need not consider the fragility of every teacup and doorknob. The structural analysis can be as sophisticated as ATC-58's multiple nonlinear dynamic analyses, or as simple as estimating roof acceleration and displacement using the N2 nonlinear pseudostatic structural-analysis method, and applying one of three schematic mode shapes to interpolate story drifts and floor accelerations.

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