DEVELOPMENT OF HAZARD-COMPATIBLE BUILDING FRAGILITY AND VULNERABILITY MODELS

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ABSTRACT :

We present a methodology for transforming the structural and non-structural fragility functions in HAZUS into a format that is compatible with conventional seismic hazard analysis information. The methodology makes use of the building capacity (or pushover) curves and related building parameters provided in HAZUS. Instead of the capacity spectrum method applied in HAZUS, building response is estimated by inelastic response history analysis of corresponding single-degree-of-freedom systems under a large number of earthquake records. Statistics of the building response are used with the damage state definitions from HAZUS to derive fragility models conditioned on spectral acceleration values. Using the developed fragility models for structural and nonstructural building components, with corresponding damage state loss ratios from HAZUS, we also derive building vulnerability models relating spectral acceleration to repair costs. Whereas in HAZUS the structural and nonstructural damage states are treated as if they are independent, our vulnerability models are derived assuming "complete" nonstructural damage whenever the structural damage state is complete. We show the effects of considering this dependence on the final vulnerability models. The use of spectral acceleration (at selected vibration periods) as the ground motion intensity parameter, coupled with the careful treatment of uncertainty, makes the new fragility and vulnerability models compatible with conventional seismic hazard curves and hence useful for extensions to probabilistic damage and loss assessment.

KEYWORDS: fragility/vulnerability model, seismic hazard, spectral acceleration, structural and nonstructural damage, repair cost / loss

1. INTRODUCTION

Building fragility functions that relate a ground motion intensity measure (e.g., spectral acceleration, S_a) to probabilities of exceeding various building damage states or performance levels, and building vulnerability functions that relate a ground motion intensity measure to probabilities of exceeding various loss levels, are integral components of any seismic risk assessment tool or study. They are used together with building inventory and ground motion intensity estimates, for a deterministic scenario earthquake or probabilistically for all possible hazardous events, to assess earthquake damage or risk for individual buildings, a portfolio of buildings, or a selected region. The results of the seismic risk assessment may be used for evaluation of different seismic design, retrofit or mitigation options, and for emergency and recovery planning.

Building fragility and vulnerability functions may be developed either for a specific building with known structural and nonstructural characteristics or for a generic building type representing a group of buildings with similar seismic design properties and configurations (Porter et al. 2001). In the former approach, building-specific fragility functions can be derived through rigorous analysis of the building response under various ground shaking levels. In the latter approach, buildings are categorized based on general characteristics such as their lateral force resisting system, height, and design code, and generic fragility functions are developed using generic structural properties and/or based on past performance of buildings. While building-specific fragility functions provide more accurate information for a particular structure, they are computationally intensive to develop and their applicability to similar buildings is questionable. On the other hand, while being less accurate or even inapplicable for a particular building, generic fragility functions can be relatively simple to develop for a large number of building types, which allows for probabilistic seismic risk assessment on a regional level. In this paper we focus on generic fragility and vulnerability functions derived by making use of the building capacity curves and related building parameters provided in HAZUS (FEMA, 2003).

Buildings considered in HAZUS are composed of three components: i) structural, ii) drift-sensitive nonstructural, and iii) acceleration-sensitive nonstructural components. The fragility functions are derived for each of these components for the four damage states considered, i.e. slight, moderate, extensive and complete. For the structural and drift-sensitive nonstructural component, the fragility functions in HAZUS are conditioned on the demand parameter of inelastic spectral displacement S_d^I, while inelastic spectral acceleration S_a^I is used for acceleration-sensitive nonstructural component. Both these parameters are calculated using the capacity spectrum method (CSM). In the CSM, the building response is determined by the intersection of a building capacity curve and a seismic demand spectrum. In HAZUS, the building capacity curves are based on engineering parameters of the structural system that characterize the nonlinear behavior of different model building types with different seismic design (code) levels. The building capacity curve is assumed to be linear up to the yield point and plastic after the ultimate strength point. The demand spectrum is based on a 5%-elastic-damping spectrum, which has a standard shape defined by $S_a(0.3\,\mathrm{sec})$ and $S_a(1.0\,\mathrm{sec})$ at the building's site. When the effective damping is higher than 5%, the elastic demand spectrum is modified by damping reduction factors using an approach similar to the CSM of ATC-40 (ATC 1996). The probabilistic damage state thresholds of the building components, defined in terms of the corresponding demand parameters, are used together with the building response estimates to estimate the probability of observing different damage states. The calculated damage state probabilities are then used to estimate the expected loss to the building using the distribution of building value among different building components determined based on its occupancy class.

This paper presents a methodology for computing fragility and vulnerability functions for generic buildings that are conditioned on S_a. We have applied the methodology and developed fragility curves for all the 36 building types and 4 seismic design levels considered in HAZUS. The methodology uses time history analysis THA as opposed to the CSM used in HAZUS. In addition to uncertainties in building capacity and damage state thresholds, effect of ground motion record-to-record variability on building response is also captured. Furthermore, the methodology accounts for non-constant variability observed in building response for given ground motion intensity. We then used these building fragility functions to derive vulnerability curves for all combinations of building types and occupancy classes considered in HAZUS. Since the derived fragility and vulnerability functions are all conditioned on S_a, they are convenient to use in seismic risk assessment studies involving generic buildings.

2. DEVELOPMENT OF BUILDING FRAGILITY MODELS

The methodology we use to develop building fragility functions, in general, follows the well-established framework of performance-based engineering (e.g. Cornell and Krawinkler 2000). As expressed in Eqn 2.1, it involves, first, probabilistic estimation of building response quantified by an engineering demand parameter EDP for a range of given intensity measure IM values and, then, estimation of building performance, defined in terms of damage state DS exceedance probabilities for a given building response.

$$P[DS \geq ds \mid IM = im] = \int_{edp} P[DST_{ds} \leq edp] f_{EDP|IM}(edp \mid im) \mathrm{d}edp \qquad (2.1)$$

where DST_{ds} is the damage state threshold for damage state ds.

As mentioned above, HAZUS fragility functions are conditioned on inelastic spectral displacement. In the context of Eqn. 2.1, they provide the damage state threshold probability distribution $P[DST_{ds} \le edp]$. The new fragility functions developed through Eqn 2.1 are conditioned on an IM compatible with existing seismic hazard data (i.e.. rates of exceedance of various IM values), namely elastic spectral acceleration. To probabilistically link S_a to inelastic spectral displacement, in this study, we use THA of equivalent SDOF systems. We use the building capacity curve parameters obtained from HAZUS to define the backbone curves for the equivalent inelastic SDOF systems; then, each system is subjected to a large number of GM records from next generation attenuation database and the peak building response or EDP (here, inelastic spectral displacement) is calculated. For the same ground motion records the relevant IM 's (e.g. elastic spectral accelerations at a number of periods) are also calculated.

The results of THA are used to estimate the probability distribution of EDP for a given IM, $f_{EDP|IM}(edp \mid im)$, through regression. This involves estimation of the median EDP given IM and the variability in EDP given IM, along with the assumption of a lognormal probability distribution. As an example that is representative of general trends, the building response and IM, in this case $S_a(0.5\,\text{sec})$, from THA are plotted in Figure 1 for a low-rise steel moment frame building designed to moderate code level. It can be seen that $\ln EDP$ vs. $\ln IM$ data exhibits a bilinear trend, with the initial portion corresponding to the elastic region and the latter portion corresponding to the behavior of the structure after yield. As also illustrated in Figure 1, the variability in building response for a given IM also exhibits a bilinear trend. It is nearly constant in the elastic region but increases with increasing IM.

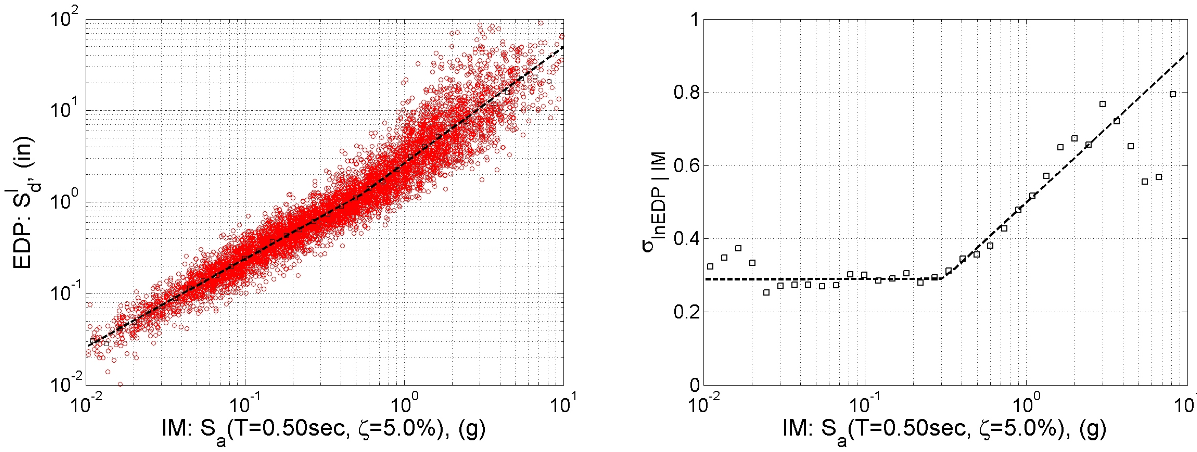

Figure 1 Regression of EDP on IM and resulting $\sigma_{\ln EDP|IM}$ for the sample moderate-code low-rise steel moment resisting frame building

We fit bilinear curves to the corresponding data to estimate the mean building response $\mu_{\ln EDP|IM}$ and the variability $\sigma_{\ln EDP|IM}$ through an iterative procedure using weighted linear least squares regression to accommodate non-constant variability, i.e. heteroscedasticity. The probabilistic building response given IM is then used together with the probabilistic damage state thresholds obtained from HAZUS (and defined in terms of EDP) to compute the fragility curves using Eqn. 2.1. Further details of the methodology can be found in Karaca and Luco (2008). The final form of the derived fragility functions are

$$P[DS \ge ds \mid IM = im] = P[(DST_{ds} - EDP) \le 0 \mid IM = im] = \Phi\left(\frac{-(\mu_{\ln DST_{ds}} - \mu_{\ln EDP|im})}{\sqrt{(\sigma_{\ln DST_{ds}})^2 + (\sigma_{\ln EDP|im})^2}} \right) \quad (2.2)$$

where $\mu_{\ln DST_{ds}}$ and $\sigma_{\ln DST_{ds}}$ represent the logarithmic damage state threshold mean and uncertainty.

Figure 2 shows the computed fragility curves for the three different components of the example building (i.e. the moderate-code low-rise steel building) for the four damage states. In general, the drift-sensitive nonstructural building component is more vulnerable than the structural component of the building for all IM ranges. The acceleration-sensitive nonstructural building component, on the other hand, is the most vulnerable of the three components at lower IM values, e.g. for $S_a(0.5\sec)$ less than 0.3g. However, the acceleration-sensitive nonstructural building component is the least vulnerable at higher IM values.

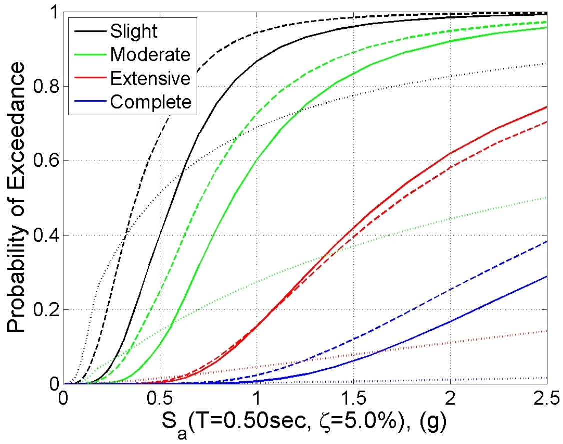

Figure 2 Computed fragility curves for structural (solid lines), nonstructural drift-sensitive (dashed lines), and nonstructural acceleration-sensitive (dotted lines) building components of the example building.

3. DEVELOPMENT OF BUILDING VULNERABILITY MODELS

In HAZUS, the building repair cost (i.e. the damage or loss) for a given damage state is expressed as a percentage of the replacement cost of the building. These repair cost ratios are assumed to be mainly dependent on the occupancy class rather than the building type, and default values are provided for each of the four damage states and the three building components – i.e. structural, nonstructural drift-sensitive and nonstructural acceleration-sensitive – of the 33 building occupancy classes. The expected loss to a given building component is calculated as the product of the building value with the weighted sum of the probabilities of the four considered damage states and the corresponding repair cost ratios. The expected loss to the building is simply the sum of the expected losses to the three building components. In this approach, nonstructural damage states are assumed to be independent of the structural damage states. However, nonstructural components, both drift- and acceleration-sensitive, may be dependent on the structural damage state – e.g. complete structural damage may cause complete nonstructural damage. For the example steel building, the complete damage state is defined as a "significant portion of the structural elements exceeding their ultimate capacities or some critical structural elements or connections failing resulting in dangerous permanent lateral displacement, partial collapse or collapse of the building." Under these conditions, the building is likely to be rebuilt independent of the condition of nonstructural components, as the building has lost its structural load carrying capacity. The definition of damage state probabilities for different building components in terms of different variables – i.e. S_a^I for the nonstructural acceleration-sensitive building component and S_d^I for the structural and nonstructural drift-sensitive components – is not amenable to consideration of such damage state correlation within the HAZUS framework.

The fragility functions for the structural and non-structural building components developed above, on the other hand, are all conditioned on the same intensity measure, i.e. spectral acceleration, allowing consideration of damage state correlations, specifically in the case of the complete structural damage state. Using the derived fragility functions (for a given building type) together with the damage/loss ratios for the four damage states for each of the three building components (for a given occupancy class) provided in HAZUS, we derive building vulnerability curves for all combinations of the 36 building types and the 33 occupancy classes. The derived vulnerability curves are all conditioned on spectral acceleration, and consider correlation of nonstructural damage states with structural damage states, specifically for complete structural damage state.

In this section, we present how the vulnerability curves are calculated from the derived fragility curves, first without considering the correlation of building component damage states, and then with consideration of this correlation. The vulnerability curves for both cases are compared and the results are discussed.

3.1. Vulnerability Models With Uncorrelated Damage States

If it is assumed that the damage or loss ratio for a given building component damage state is constant, then the number of possible damage ratios for a building component are equal to the number of considered damage states. For example, in HAZUS and in this study, five damage states (including no damage) are considered for each of the three building components. This assumption further implies that the probability of observing the i th damage ratio $DR(i)$ is equal to the probability of being in the corresponding damage state, i.e.

$$P[DR(i) \mid IM] = P[DS(i)] \mid IM] = P[DS = i \mid IM = im] \tag{3.1}$$

where i=1 for no damage, 2 for slight damage, 3 for moderate damage, 4 for extensive damage, and 5 for complete damage. For each of the three building components, the discrete damage state probabilities at a given IM level are obtained from the probabilities of exceedance of damage states, i.e. the derived fragility curves. using

$$P[DS(i) \mid IM] = \begin{cases} 1 - P[DS \geq i+1 \mid IM = im] & \text{for } i = 1 \\ P[DS \geq i \mid IM = im] - P[DS \geq i+1 \mid IM = im] & \text{for } i = 2,3,4 \\ P[DS \geq i \mid IM = im] & \text{for } i = 5 \end{cases} \tag{3.2}$$

If it is further assumed that the damage state probabilities of the building components are uncorrelated, then the number of possible damage ratios for the building is simply equal to the number of possible damage states raised to the power of the number of building components, in this case 125. If we denote the building damage ratio corresponding to the i th structural component damage state, j th drift-sensitive nonstructural component damage state, and k th acceleration-sensitive nonstructural component damage state by $DR^{BLDG}(i,j,k)$, then

$$DR^{BLDG}(i,j,k) = DR^{STR}(i) * VR^{STR} + DR^{NSD}(j) * VR^{NSD} + DR^{NSA}(k) * VR^{NSA} \tag{3.3}$$

where VR^{STR}, VR^{NSD}, and VR^{NSA} denote the percentage of the replacement value of the building assigned to structural (STR), drift-sensitive nonstructural (NSD), and acceleration-sensitive nonstructural (NSA) components, respectively.

Under this assumption of no correlation, the corresponding probability of observing $DR^{BLDG}(i,j,k)$ at a given IM level is

$$P[DR^{BLDG}(i,j,k) \mid IM] = P[DR^{STR}(i) \mid IM] * P[DR^{NSD}(j) \mid IM] * P[DR^{NSA}(k) \mid IM] \tag{3.4}$$

If we sort the damage ratios $DR^{BLDG}(i,j,k)$ in ascending order, keeping track of their corresponding probabilities, we obtain a vector of building loss ratios, denoted lr, with values increasing from 0 to 1.0. Then we can express our final vulnerability model either as a conditional probability mass function, $P[LR \mid IM]$, or in terms of a conditional cumulative probability distribution function, $P[LR \geq lr \mid IM]$.

In many cases, the vulnerability model is used to obtain vulnerability curves or functions that give the mean and standard deviation of damage/loss ratios at a given *IM* value, i.e.

$$\mu[LR \mid IM] = \sum_i P[LR = lr(i) \mid IM] * lr(i) \quad (3.5)$$

$$\sigma[LR \mid IM] = \sqrt{\sum_i P[LR = lr(i) \mid IM] * (lr(i) - \mu[LR \mid IM])^2} \quad (3.6)$$

3.2. Inclusion of Damage State Correlation in Vulnerability Model

If instead it is assumed that complete damage of the structural component also causes replacement or loss of the nonstructural components, then the probability of observing a certain damage ratio for a nonstructural component becomes dependent on the damage state of the structural component (in addition to the damage state of that nonstructural component). For example, the with-correlation probabilities for the nonstructural drift-sensitive component remain a function of its damage state, as given in Eqn 3.1, for structural damage states other than complete, i.e.

$$P[DR_{Corr}^{NSD}(j) \mid IM] = P[DS^{NSD}(j) \mid IM] \quad \text{for j} = 1,\ldots,5 \ \& \ DS^{STR} = 1,\ldots,4 \quad (3.7)$$

On the other hand, for the complete structural damage state, it becomes

$$P[DR_{Corr}^{NSD}(j) \mid IM] = \begin{matrix} 0 & \text{for j} = 1,\ldots,4 \ \& \ DS^{STR} = 5 \\ 1 & \text{for j} = 5 \quad \& \ DS^{STR} = 5 \end{matrix} \quad (3.8)$$

This dependence can be introduced into the vulnerability model by modifying the corresponding entries of the discrete joint probability distribution expressed in Eqn 3.4 to obtain $P[DR_{Corr}^{BLDG}(i,j,k) \mid IM]$. Again, the final vulnerability model can be expressed as a conditional probability mass function, $P[LR_{Corr} \mid IM]$. Note that in this case some of the values of the conditional probability mass function will be equal to 0.

3.3. Sample Results and Discussion

In this section we present sample results for the example moderate-code low-rise steel moment resisting frame building of HAZUS. We assume a HAZUS occupancy class of commercial (labeled COM4), which in turn assumes that the structural component accounts for 19.2% of building replacement costs, while the drift- and acceleration-sensitive nonstructural components account for 32.9% and 47.9% of building replacement costs, respectively. Curves for mean loss ratios and the corresponding coefficients of variation of loss calculated for this example building with and without correlation among nonstructural and structural components are plotted in Figure 3. These curves are obtained from the fragility curves plotted in Figure 2 using the above methodology and formulation. As expected, for both cases (correlated and uncorrelated) the mean loss ratios increase with increasing intensity, while the coefficients of variation in loss show the opposite behavior and generally decrease with increasing intensity. Introduction of correlation results in an increase in mean loss ratio at higher spectral accelerations, especially for *IM* values greater than 1.0g. The correlation does not have any effect on the vulnerability curve at lower *IM* values, as the probability of observing complete damage for the structural component is near zero (see Figure 2). The introduction of correlation also results in an increase in the coefficient of variation of loss.

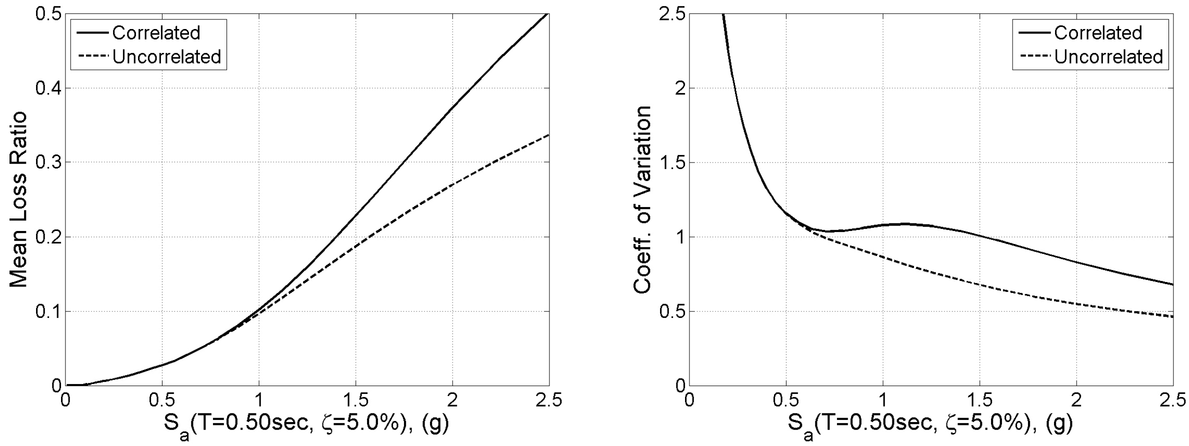

Figure 3 Mean loss ratios and corresponding coefficients of variation for the example building.

The vulnerability curves for the building are re-plotted in Figure 4, along with the mean loss ratios for the individual building components, with and without considering the correlation. While the vulnerability curves for the structural component are identical, in the presence of correlation the mean loss ratios for the nonstructural components are higher at *IM* values higher than 1.0g, due to reasons explained above. For example, at an *IM* value of 2.0g, the mean loss ratio of drift-sensitive nonstructural components increase from 0.45 to 0.54, while that for acceleration-sensitive nonstructural components increase from 0.08 to 0.23.. This is also reflected in the overall vulnerability curves for the building, e.g. the mean loss ratio at an *IM* value of 2.0g increases from 0.27 to 0.37. Also, the inclusion of correlation has (at higher *IM* values) more influence on the nonstructural acceleration-sensitive component, i.e. the less vulnerable of the two nonstructural components. The effect of correlation on the vulnerability of the drift-sensitive nonstructural component is less pronounced as it is not only more vulnerable than the acceleration-sensitive nonstructural component, but also than the structural component at higher *IM* values.

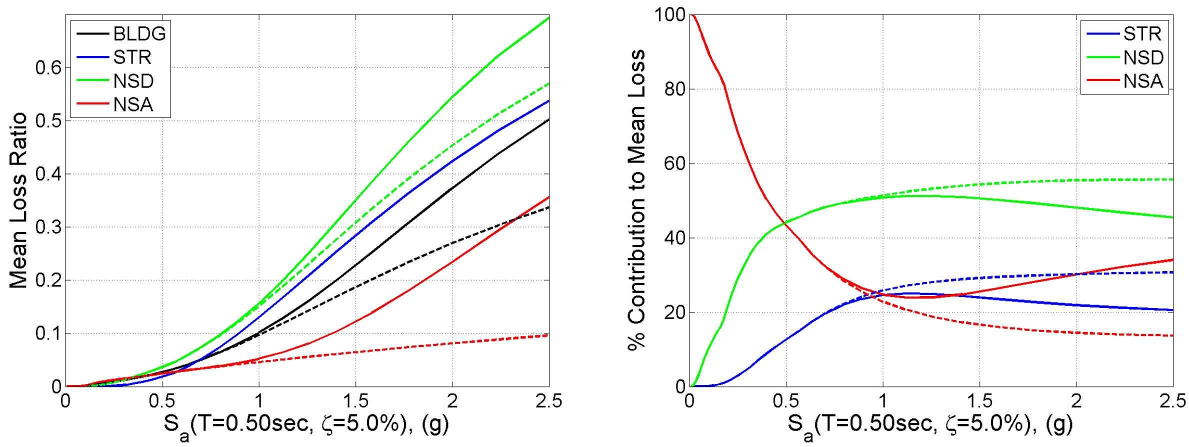

Figure 4 Mean loss ratios of building components with (solid lines) and without (dashed lines) correlation and their relative contribution to mean loss.

Figure 4 also shows the relative contributions of the three building components to the overall mean loss ratio of the building. At lower *IM* levels, i.e. approximately up to 0.45g, the biggest contribution to the mean building loss is from the acceleration-sensitive nonstructural component, mainly due to higher vulnerability of this component at these *IM* levels and, to some extent, its higher share of the total building replacement cost compared to the other building components. However, with increasing *IM* values, the contribution of the acceleration-sensitive building component decreases while those of the drift-sensitive nonstructural component and the structural component generally increase. At higher *IM* values, the drift-sensitive nonstructural component has the biggest contribution to loss, due both to its higher vulnerability and its relatively significant share of the total building replacement cost. With the introduction of correlation, on the other hand, the contribution of the acceleration-sensitive nonstructural component increases significantly, while those for the other two components decrease as the vulnerability of acceleration-sensitive nonstructural components, which have the largest contribution to the building value, increases significantly. It is interesting to note that the structural component has limited contribution to loss, as less than 20% of the total replacement cost is directly associated with this component. However, it has an indirect but significant influence on the overall building loss at higher *IM* levels, since the vulnerabilities of the nonstructural components are dependent on the damage to the structural component.

4. CONCLUSION

We have developed a methodology for transforming the structural and non-structural fragility functions in HAZUS into a format that is compatible with conventional seismic hazard analysis information. This allows for convenient use of these curves in probabilistic seismic loss estimation studies such as Wesson et al, 2008._The developed methodology introduces several improvements to the models currently used in HAZUS, such as the use of inelastic time history analysis to estimate building response, use of spectral acceleration as the intensity measure (IM) for the fragility curves of all building components, and improved treatment of uncertainty including that_in building response due to ground motion record-to-record variability. The developed fragility models for structural and nonstructural building components, with corresponding damage state loss ratios from HAZUS, are used to derive building vulnerability models relating spectral acceleration to repair costs, both under the assumption that the structural and nonstructural damage states are independent, and by assuming "complete" nonstructural damage whenever the structural damage state is complete. The effects of considering this dependence on the final vulnerability models are illustrated for an example low-rise steel moment frame building. At low IM values, the probability of complete structural damage is close to zero and the introduction of this dependence do not affect the vulnerabilities of the nonstructural components or the building. However, at higher IM values, the vulnerabilities of both drift-sensitive and acceleration-sensitive nonstructural components increase significantly. The effect on the latter is more pronounced as vulnerability of acceleration-sensitive nonstructural components is lower than that of structural components at this IM range, while drift-sensitive nonstructural components is less vulnerable than structural components.

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