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INFLUENCE OF RESIDUAL DISPLACEMENTS ON BUILDING LOSS ESTIMATION

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ABSTRACT

The influence of residual interstory drifts on economic losses in building resulting from earthquakes is evaluated. A new approach to incorporate residual interstory drifts is presented. The new approach explicitly accounts for the probability of having to demolish a building as a function of residual interstory drifts. The proposed approach is illustrated by estimating direct economic seismic losses in four reinforced concrete moment resisting frame buildings in Los Angeles, California. Two buildings have non-ductile detailing representative of pre-70's building codes while the other two buildings have ductile requirements satisfying current seismic building codes in the U.S. Results from this study indicate that economic losses at intermediate levels of ground motion intensity are often dominated by losses due to residual interstory drifts. This is particularly true in the case of ductile buildings which have a larger deformation capacity and therefore smaller probability of collapse during intense ground motions, but have a considerable probability of experiencing residual displacements. It is concluded that neglecting losses from residual drifts can lead to significant underestimation of economic losses.

Introduction

Current building-specific loss estimation methodologies typically estimate economic losses based only on peak response quantities such as peak interstory drift ratios or peak floor accelerations (Porter and Kiremdjian 2001; Krawinkler and Miranda 2004; Miranda et al. 2004; Aslani and Miranda 2005, Mitriani-Rieser 2007).

However, in addition to peak interstory drift demands and peak floor accelerations, residual deformations also play a crucial role in defining the performance of a structure and can have important consequences. In particular, the amplitude of residual deformations is critically important in determining the technical and economical feasibility of repairing damaged structures. For example, several dozen damaged reinforced concrete buildings in Mexico City had to be demolished after the 1985 Michoacan earthquake because of the technical difficulties to straighten and repair buildings with large permanent drifts (Rosenblueth and Meli, 1986). Similarly, many reinforced concrete bridge piers were demolished in the city of Kobe in Japan after the 1995 Hyogo-Ken-Nambu earthquake due to the technical difficulties and elevated costs that would be required to straighten and repair piers with large permanent lateral deformations (Kawashima 2000).

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Figure 1. Examples of buildings with residual displacements leading that typically lead to demolition (left photo by M. Bruneau, MCEER; right photo by A. Whittaker, NISEE, EERC, UC Berkeley).

Recent analytical and experimental studies (Mahin and Bertero 1981, MacRae and Kawashima 1997, Pampanin et al. 2002, Ruiz-Garcia and Miranda 2005) have shown that the structures subjected to large inelastic deformations have a very high probability of experiencing residual deformations (see figure 1). This suggests that ductile lateral force resisting systems which are designed and detailed to be able to sustain large lateral displacements without collapse are specially more likely to experience residual deformations when subjected to intense seismic ground motions which may lead to a total loss of stakeholder investments despite the avoidance of collapse.

The objective of this paper is to present a summary of an improved loss estimation methodology that explicitly incorporates economic losses resulting from the possibility of having to demolish buildings that have experienced large residual interstory drifts. The improved methodology is illustrated by computing economic losses in four reinforced concrete moment-frame buildings. In each case economic losses are estimated with the existing loss estimation methodologies and the proposed approach.

Improved Loss Estimation Methodology

In recently proposed loss estimation methodologies (Krawinkler and Miranda 2004; Miranda et al. 2004; Aslani and Miranda 2005, Mitriani-Rieser 2007) expected losses at a given level of ground motion intensity are computed as

$$E[L_T \mid IM] = E[L_T \mid NC, IM] \cdot P(NC \mid IM) + E[L_T \mid C] \cdot P(C \mid IM) \tag{1}$$

where $E[L_T \mid NC, IM]$ is the expected value of the economic loss associated with necessary repairs due to the damage sustained in the building given that it has not collapse when subjected to a ground motion with intensity $IM=im$; $E[L_T \mid C]$ and $E[L_T \mid C]$ is the expected value of the loss when the building collapses; and $P(NC \mid IM)$ and $P(C \mid IM)$ are the probabilities of not experiencing a collapse and of collapsing when the building is subjected to a ground motion with intensity $IM=im$, respectively.

While Eq. (1) appears to account for all possible losses it fails to recognize that the building may have to be demolished and therefore lead to a total loss even it it has survived the earthquake without collapse. Based on the total probability theorem the authors have improved Eq. (1) to compute the expected value of the total economic loss in a building conditioned on a ground motion intensity $IM=im$, $E[L_T \mid IM]$, as the weighted sum of expected losses in three mutually exclusive, collectively exhaustive events. Namely: (1) collapse does not occur (non-collapse, NC) and damage in the building is repaired, R, (i.e., $NC \cap R$); (2) collapse does not occur but the building is not repaired, NR, and it is subsequently demolished and rebuilt, (i.e., $NC \cap D$); and (3) collapse occurs and the building is rebuilt, C. The expected value of the loss in the building for a given ground motion intensity $IM=im$ is computed as

$$E[L_T \mid IM] = E[L_T \mid NC \cap R, IM]P(NC \cap R \mid IM) + E[L_T \mid NC \cap D]P(NC \cap D \mid IM) + E[L_T \mid C]P(C \mid IM) \quad (2)$$

where $E[L_T \mid NC \cap R, IM]$ is the expected value of the total loss in the building given that collapse does not occurs (non-collapse) and the building is repaired knowing that it has been subjected to earthquakes with a ground motion intensity $IM=im$, $E[L_T \mid NC \cap D]$ is the expected loss in the building when there is no collapse but the building is demolished, and $E[L_T \mid C]$ is the expected loss in the building when collapse occurs in the building. The weights on these three expected losses are $P(NC \cap R \mid IM)$ which is the probability that the building will not collapse and that it will be repaired given that it has been subjected to earthquakes with a ground motion intensity $IM=im$, $P(NC \cap D \mid IM)$ is the probability that the building will not collapse but that it will have to be demolished given that it has been subjected to earthquakes with a ground motion intensity $IM=im$, and $P(C \mid IM)$ is the probability that the structure will collapse under a ground motion with a level of intensity, im. Comparing equations (1) and (2) it is then clear that previous building-specific loss estimation investigations (Miranda et al. 2004; Aslani and Miranda, 2004; Haselton et al., 2005) neglected the intermediate term and given that, in general, this term is larger than zero, a systematic underestimation in losses was produced.

The probability that the building will not collapse and that it will be repaired given that it has been subjected to earthquakes with a ground motion with a level of intensity, im is given by

$$P(NC \cap R \mid IM) = P(R \mid NC, IM) \cdot P(NC \mid IM) \quad (3)$$

Similarly, the probability that the structure will not collapse but that will need to be demolished when subjected to a ground motion with intensity level $IM=im$ is computed as

$$P(NC \cap D \mid IM) = P(D \mid NC, IM) \cdot P(NC \mid IM) \quad (4)$$

where $P(D \mid NC,IM)$ is the probability that the structure will be demolished given that it has not collapsed when subjected to an earthquake ground motion with intensity level $IM=im$ and $P(NC|IM)$ is the probability of no collapse when the building is subjected to an earthquake ground motion with intensity level $IM=im$.

Since repair and demolition events given that no collapse has occurred are mutually exclusive events (i.e., if the structure survives the earthquake without collapse you either demolish it or not) and collapse and non-collapse are also mutually exclusive events (i.e., the structure will either collapse or not collapse during an earthquake) then

$$P(R \mid NC, IM) = 1 - P(NR \mid NC, IM) \tag{5}$$

$$P(NC \mid IM) = 1 - P(C \mid IM) \tag{6}$$

Substituting (5) and (6) into (4) we obtain

$$P(NC \cap D \mid IM) = P(D \mid NC, IM) \cdot \{1 - P(C \mid IM)\} = P(D \mid NC, IM) - P(D \mid NC, IM) \cdot P(C \mid IM) \tag{7}$$

Finally substituting (3) and (7) into (2) we have

$$\begin{aligned} E[L_T \mid IM] = {} & E[L_T \mid NC \cap R, IM] \cdot \{1 - P(D \mid NC, IM)\} \cdot \{1 - P(C \mid IM)\} \\ & + E[L_T \mid NC \cap D] \cdot P(D \mid NC, IM) \cdot \{1 - P(C \mid IM)\} + E[L_T \mid C] \cdot P(C \mid IM) \end{aligned} \tag{8}$$

Estimating the probability that the structure will need to be demolished given that it has not collapsed is particularly challenging because of the many factors that may be involved in arriving to such decision. In the proposed methodology we estimate such probability as a function of residual lateral deformations. Experience after the 1985 Mexican earthquake, the 1995 Hyogo-ken-Nambu (Kobe) earthquake and other earthquakes indicates that permanent (residual) lateral deformation was the primary factor driving the decision to demolish buildings and other structures even when damage was with relatively small. In the proposed approach the probability of having to demolish a building that has not collapsed given that it has been subjected to an earthquake ground motion with intensity *IM=im* is computed as a function of the peak residual interstory drift ratio as follows:

$$P(D \mid NC, IM) = \int_0^\infty P(D \mid RIDR)\, dP(RIDR \mid NC, IM) \tag{9}$$

where $P(D|RIDR)$ is the probability of having to demolish the structure conditioned on the peak residual interstory drift in the building (maximum from all stories in the building) and $P(RIDR|NC,IM)$ is the probability of experiencing a certain level of residual interstory drift ratio in the building given that it has not collapsed and that it has been subjected to a ground motion with intensity *IM=im*. Eq. (5) considers that there is variability in the decision to demolish a building for a given level of residual interstory drift. This probability may be interpreted as the percentage of engineers that would recommend demolition of the building for a given of residual interstory drift. Based on limited information and on engineering judgment we have assumed $P(D|RIDR)$ to be lognormally distributed with a median of 0.015 and a logarithmic standard deviation of 0.3. The resulting cumulative probability distribution is shown in figure 2. As shown in this figure, buildings with a residual interstory drift ratio of 1% would have a small probability of having to be demolished and buildings experiencing residual interstory drift ratios larger than 3% would practically be certain that they would have to be demolished.

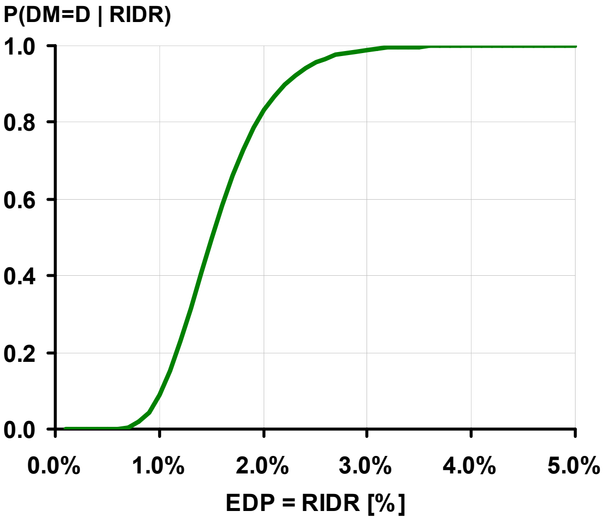

Figure 2. Probability of having to demolish a building that has not collapsed as a function of the peak residual interstory drift in the building.

Application of the Proposed Methodology

The proposed improved loss estimation methodology was used to evaluate economic losses in four reinforced concrete frame buildings whose seismic response was previously studied by other investigators (Haselton and Deierlein, 2007; Liel and Dierlein, 2008). The four case study buildings are: a 4-story building with ductile detailing, a 12-story building with ductile detailing, a 4-story building with non-ductile detailing, and a 12-story building with non-ductile detailing. All four structures were assumed to be located at a site in Los Angeles, CA, south of the city's downtown area, and is representative of a typical urban California site with high levels of seismicity, but not subject to near-fault directivity effects. The two structures with ductile detailing were modern buildings designed by Haselton and Deierlein (2007) according to the 2003 International Building Code and related ACI and ASCE provisions (ACI 2002, ASCE 2002, ICC, 2003). The two non-ductile buildings were designed according to the 1967 Uniform Building Code (UBC 1967) and are representative of older concrete frame structures built in California from approximately 1950 to 1975. For detailed information on the designs and modeling parameters of these structures the reader is referred to Liel and Deierlein (2008).

The reinforced concrete frame structures were modeled in OpenSees (PEER, 2006) using a two-dimensional, three-bay model of the lateral resisting system and a leaning (P-Δ) column. Beams and columns were modeled with concentrated hinge (lumped plasticity) elements and employ a material model developed by Ibarra et al. (2005). The nonlinear simulation models of the reinforced concrete frames were analyzed by Haselton and Liel using the incremental dynamic analysis technique by analyzing each model using a large set of ground motions scaled at increasing levels of ground motion intensity. Subsequently economic losses were computed using the story-based approach suggested by the authors (Ramirez and Miranda, 2009). In each case economic losses were computed considering without considering the intermediate term in Eq (2) and considering this intermediate term in order to evaluate its influence in economic losses. The influence of this term was evaluated for each building by comparing expected losses at increasing levels of ground motion intensity, by comparing expected annual losses and by comparing the probability of exceedance of large economic losses.

Figure 3 compares the expected economic losses with and without considering losses due to the possibility of having to demolish the 4-story ductile building for three different levels of seismic hazard. The first pair corresponds to a service level earthquake with a 50% probability of occurrence in 50 years. The middle pair of bars corresponds to the expected economic losses at the Design Basis Earthquake (DBE) defined as the intensity with a 10% of occurrence in 50 years and the pair to the right corresponds to the losses due to seismic event that has a probability of exceedance of 2% in 50 years (often referred to as the Maximum Credible Earthquake, MCE). The values of the seismic ground motion intensity that correspond to all three hazard levels are indicated at the bottom of the figure. Expected values are normalized by the replacement cost of the structure.

For each hazard level, the left bar corresponds to losses that do not considering losses due demolition and the right bar corresponds to the losses that consider losses due to demolition. It can be seen that at the service-level earthquake, the effect of losses due to building demolition does not have an influence on the overall normalized loss. On the other hand, the normalized economic losses increase from 31% to 42% at the DBE and from 48% to 73% at the MCE corresponding to increments in expected losses of 35% and 52% and the DBE and MCE levels,

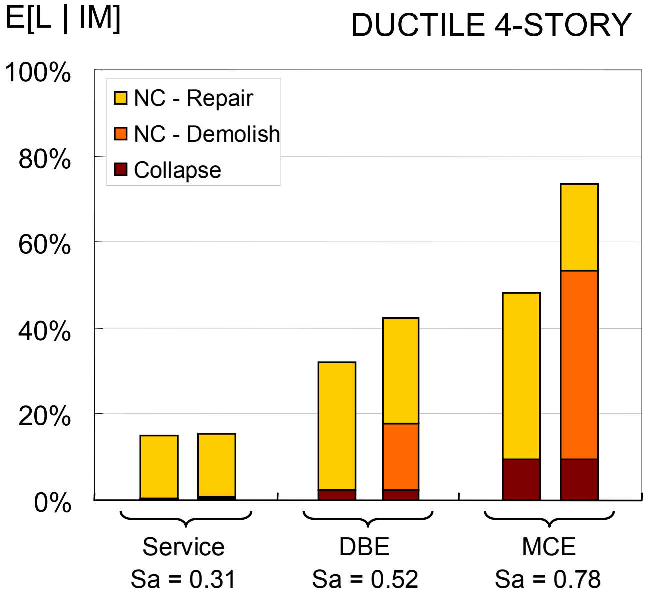

Figure 3. Comparison of expected losses in a four-story MRF building designed according to the 2003 IBC computed without the inclusion of the possibility of demolition and including the possibility of demolition.

respectively. The relative increase is the difference between the two values of expected loss, with and without considering losses due to demolition, divided by the expected loss with considering losses due to demolition, multiplied by 100. This means that losses due to demolition have a large influence in the overall loss estimate, and that neglecting these losses can lead to significant underestimations in economic losses.

To gain further understanding of the influence of the possibility of having to demolish a building after an earthquake even though it has not collapse loss results at these levels were disaggregated following the approach proposed by Aslani and Miranda, (2005). In figure 3 each bar in the figure is divided up into collapse losses, non-collapse (NC) losses due to building demolition and non-collapse losses due to repair costs. The proportions of each bar are equal to how much each type of loss contributes to the overall loss. As shown in this figure, demolition losses have the largest contributions to the overall loss at the MCE. At this intensity level, losses conditioned on non-collapse due to demolition dominate the expected loss. In particular, the losses due to demolition are significantly larger than those of collapse even though both lead to total loss of the initial investment. This is because at the MCE, the probability of demolition is much higher (45%) than the probability of collapse (8%), that is, at this level of ground motion intensity the structure is more likely to experience large residual deformations that will lead to demolition, than collapsing.

Expected economic losses computed with and without considering losses due to the possibility of having to demolish the 4-story non-ductile building for three different levels of seismic hazard are presented in figure 4. It can be seen that for this structure losses due to

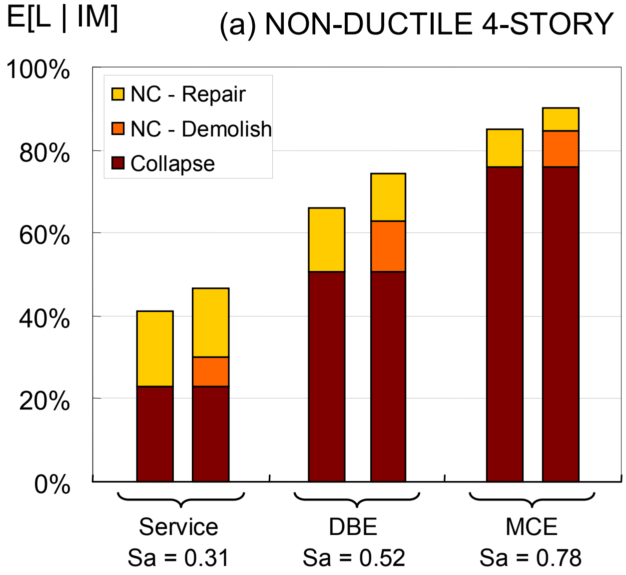

Figure 4. Comparison of expected losses in a non-ductile four-story MRF building designed according to the 1967 UBC computed without the inclusion of the possibility of demolition and including the possibility of demolition.

collapse dominate economic losses even for the service level earthquake. Similar to the ductile building, neglecting losses due to possible demolition leads to underestimation of economic losses, but in this case the underestimations are much smaller. For example, at the DBE the increase in loss when losses due to demolition are accounted for in the non-ductile building is only 12% while the increase in the ductile structure was 35% increase. This is because non-ductile structures have semi-brittle behaviors and the probability of undergoing large inelastic deformations without collapse is usually smaller than the probability of collapse even for moderate ground motion intensities. Similar results were computed for the 12-story building, but due to space limitations only results for the 4-story building are presented here. Results for the 12-story ductile and non-ductile buildings are available at Ramirez and Miranda, 2009.

Summary and Conclusions

The Pacific Earthquake Engineering Research (PEER) Center methodology for seismic performance assessment has been extended to explicitly account for the possibility of having to demolish a building that did not collapse during an earthquake. In the proposed framework the probability of having to demolish the building given that it has not collapsed is computed as a function of the peak residual interstory drift in the building conditioned on the ground motion intensity. The latter is computed by conducting and incremental dynamic analysis in which peak residual interstory drifts are computed at increasing levels of ground motion intensity. By doing so, the record-to-record variability of residual drift demands is explicitly taken into account.

Results indicate that neglecting the probability of demolition due to excessive residual lateral deformations as typically done presently leads to significant underestimations of economic losses. Underestimations are typically larger in ductile buildings than in non-ductile buildings. This is because ductile structures are very effective in reducing the probability of collapse when subjected to intense ground motions, but they have a significant probability of having to be demolished due to residual drifts. Meanwhile, when non-ductile structures are subjected to intense ground motions they typically have a relatively large probability of collapse and the probability of surviving the earthquake with large permanent deformations that will lead to demolition is much smaller.

The proposed framework provides an ideal tool to assess the tradeoffs and benefits of various design alternatives. In particular it provides a framework to properly account for the economical benefits of incorporating self-centering technologies with significantly reduce or even eliminate residual drifts.

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