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REGIONAL RISK ASSESSMENT FOR SEISMIC DESIGN ALTERNATIVES – THE CASE OF MEMPHIS, TENNESSEE

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ABSTRACT

The 2003 International Building Code (IBC) has been adopted and is currently used for the design of buildings in Memphis, Tennessee, but, it has been amended to allow the use of lower ground motion values or the earthquake provisions of the previously-used building code - i.e. the 1999 Southern Building Code (SBC) - for seismic design of non-essential buildings. Through a regional risk assessment study for Memphis, we have evaluated the implications of adopting each of the following seismic code options: 1) 2009 NEHRP Recommended Provisions, 2) 2006 IBC, 3) 2003 IBC, 4) amended 2003 IBC, and 5) 1999 SBC. As the building codes apply mainly to new buildings, we simulated a portfolio of buildings on currently-vacant parcels in Memphis considering local zoning requirements and the structural characteristics of nearby existing buildings. For each building, we derived the vulnerability models representing the design options based on both i) the simulated structural characteristics of the building and ii) the design ground motions and corresponding seismic design or performance categories specified by the codes (see Karaca and Luco, 2009). Then, we computed the expected annual loss for each building, by coupling the vulnerability of the building and hazard curve at the location of the building. The total expected annual loss for each seismic design option is computed by taking the sum across the portfolio buildings. Similarly, we also computed the total expected losses due to two scenario earthquakes. The results illustrate that risks are significantly higher for design based on the amended 2003 IBC compared to the other design options.

Introduction

The International Building Code (IBC) has been adopted by most of the jurisdictions in the U.S. However, there remains some resistance to the adoption of its earthquake provisions in the Central U.S. (CUS), mainly due to the thought that the earthquake risk is lower than suggested by the Maximum Considered Earthquake (MCE) ground motion maps in the IBC. While the 2003 IBC is currently being used for the design of buildings in Memphis, Tennessee, it has been amended to allow the use of lower ground motion values or the earthquake provisions

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of the previously-used building code - i.e. the 1999 Southern Building Code (SBC) - for seismic design of non-essential buildings.

Through a regional risk assessment study for Memphis, we have evaluated the implications of adopting each of the following seismic code options: 1) 2009 NEHRP Recommended Provisions, 2) 2006 IBC, 3) 2003 IBC, 4) amended 2003 IBC, and 5) 1999 SBC. The work involved derivation of loss-versus-ground-motion vulnerability models for buildings (of different structural types and heights) designed according to each of the seismic code options and calculation of potential earthquake-induced losses to a portfolio of buildings. As the building codes apply mainly to new buildings, we simulated a portfolio of buildings on currently-vacant parcels in Memphis considering local zoning requirements and the structural characteristics of nearby existing buildings. For each building, we derived the vulnerability models representing the design options based on both i) the simulated structural characteristics of the building and ii) the design ground motions and corresponding seismic design or performance categories specified by the codes (see Karaca and Luco, 2009). Then, we computed the expected annual loss for each building, by coupling the vulnerability of the building and hazard curve at the location of the building. The total expected annual loss for each seismic design option is computed by taking the sum across the portfolio buildings. Similarly, we also computed the total expected losses due to two scenario earthquakes. The results illustrate that risks are significantly higher for design based on the amended 2003 IBC compared to the other design options.

Study Area

The City of Memphis and surrounding Shelby County lie within the New Madrid Seismic Zone, which extends from northeast Arkansas, through southeast Missouri, western Tennessee, and western Kentucky to southern Illinois. Historically, this area has been the site of some of the largest earthquakes in North America. Earthquakes with magnitudes greater than 7.0 occurred in this area between 1811 and 1812. The estimated recurrence interval of a moment magnitude 7.0 or larger earthquake is approximately 500 years (Gomberg and Schweig, 2002). Metropolitan Memphis has a dense urban population near faults capable of producing major earthquakes, a 25-40% probability of being affected by a magnitude 6.0 or greater earthquake in the next 50 years (Gomberg and Schweig, 2002). Furthermore, the central United States has a relatively low regional attenuation. In other words, seismic energy can travel faster than in the west and thus an earthquake can cause damage over a greater area than for the same magnitude earthquake in the western U.S.

Building Portfolio

Using the built-on and vacant land parcels in Shelby County and the existing building portfolio developed by French and Muthukumar (2006, personal communcation), a hypothetical portfolio of future commercial buildings on vacant parcels was simulated. The zoning assigned to each of the existing buildings in the portfolio was determined using parcel data provided by Shelby County. Then, for each of the vacant parcels, possible buildings that could be built on the parcel based on existing buildings with the same zoning code were simulated. For a given vacant parcel, the assigned building type was chosen by selecting it at random from the 50 closest existing buildings with the same zoning code as the vacant parcel. A check of whether the randomly selected building fits in the area of the vacant parcel was performed, and if it did not fit then another building was randomly selected. Only one building was selected for each vacant parcel. Figure 1a) shows the occupied parcels and existing buildings, and Figure 1b) shows the vacant parcels and simulated buildings, respectively.

The properties of each building include number of stories, structure type, occupancy type, replacement cost, contents value, total value (i.e. replacement cost plus contents value), zoning, and land value. All of the properties of the simulated buildings are taken to be the same as those of the randomly-selected existing building except the replacement cost. The building portfolio developed by French and Muthukumar (2006, personal communication) has replacement costs assigned to the existing buildings, but their variability is surprisingly large, so alternatively replacement costs were assigned using unit cost data from HAZUS (FEMA, 2003) and the square footage of the buildings.

The vacant parcels considered for projecting future commercial or industrial buildings are limited to the following zoning codes: light or heavy industry; planned, local, or highway commercial; central business; and limited or general office. The total number of vacant parcels within these zoning codes is 5,118. Agricultural parcels are not included even though some of the commercial or industrial buildings in the building portfolio used are located on existing agricultural parcels. The total value of the portfolio was estimated at US$ 6.8B. The most number of buildings in the portfolio consists of reinforced masonry bearing walls with wood or metal deck diaphragms (labeled RM1L in HAZUS) whose occupancy class is retail trade (labeled COM1 in HAZUS), followed by steel light frame building (labeled S3 in HAZUS) whose occupancy class is wholesale trade (labeled COM2 in HAZUS). And building with the highest total value by the structure type and the occupancy class is steel light frame building (S3) with whole trade (COM2) occupancy class.

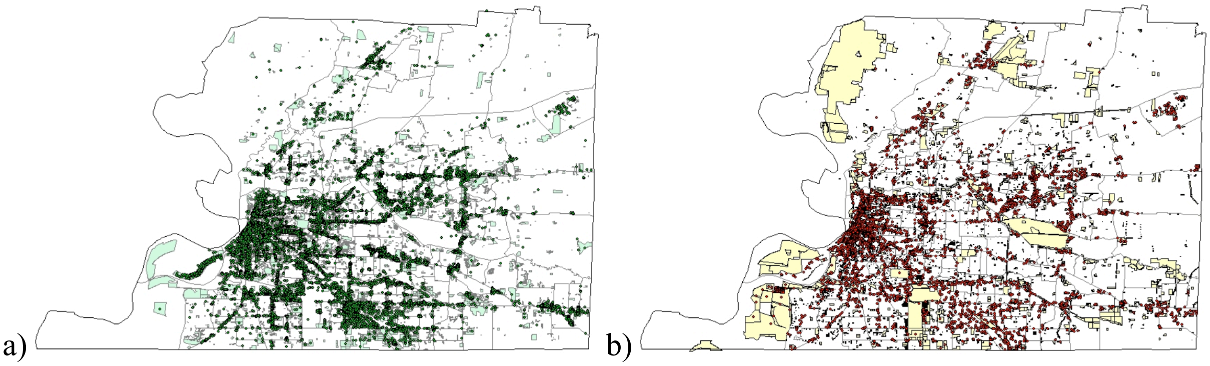

Figure 1. Simulated building portfolio. Panel a) shows the occupied parcels and existing buildings, and panel b) shows the vacant parcels and simulated buildings, respectively.

Ground Motion Hazard

Considering the potential for earthquakes and the low regional attenuation mentioned in the preceding section, the USGS has developed so-called urban seismic hazard maps for Memphis/Shelby County, Tennessee (http://earthquakes.usgs.gov/regional/ceus/products/grid_download.php) in which local site conditions was reflected through site specific amplification (Cramer et al., 2004). Analogous but less region-specific hazard maps have also been developed by the USGS for the entire U.S. and its territories (http://earthquake.usgs.gov/hazmaps). These maps are interpolated from seismic hazard curves that report the mean annual frequencies of exceedance (roughly equal to annual exceedance probabilities) computed via probabilistic seismic hazard analysis (PSHA) for each in a range of ground shaking intensity levels. Figure 2 shows Memphis urban hazard and site adjusted US hazard curves at the City of Memphis (-89.97, 35.12) for spectral accelerations at 0.5 sec, and 1.0 sec, respectively, on which the derived vulnerability models are conditioned. The site adjusted US hazard curves were derived by adjusting the US hazard curves (Petersen et al., 2008) to the site class *D* using the NEHRP site amplification factors. Note that the US hazard curves are defined for the site class B/C boundary.

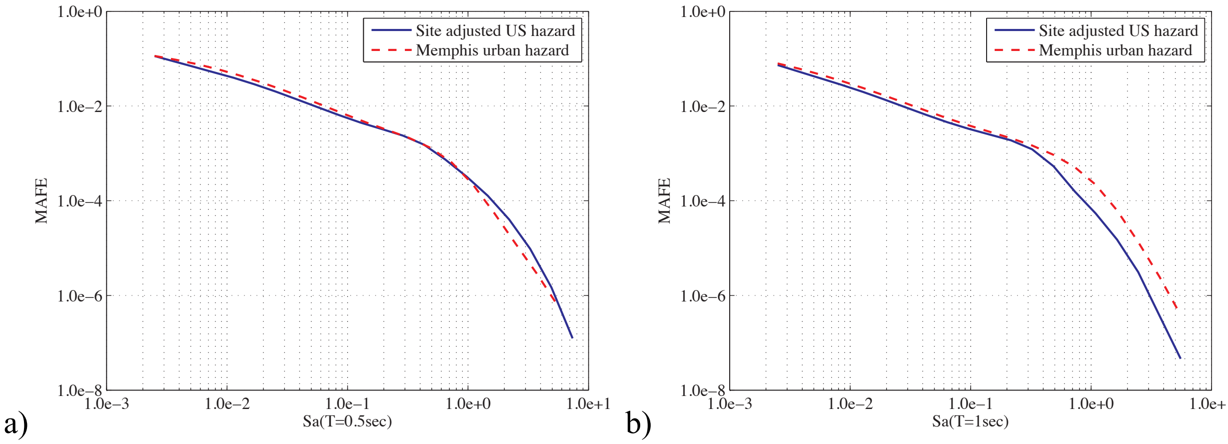

Figure 2. Memphis urban hazard and site adjusted US hazard curves for a) spectral acceleration at 0.5 sec, and b) spectral acceleration at 1 sec.

Seismic Design Alternatives

For the regional risk assessment of the study area, we consider the five seismic code options: 1) 2009 NEHRP Provisions, 2) 2006 IBC, 3) 2003 IBC, 4) amended 2003 IBC, and 5) 1999 SBC. In the following, we summarize how to determine seismic response or design coefficient, C_s, and seismic design or performance category by the seismic code options, which will be used to derive seismic vulnerability models for buildings. Also we summarize how to determine the design spectral response accelerations by all codes except 1999 SBC, and the seismic coefficients by 1999 SBC.

Determination of Seismic Response or design Coefficient (C_s)

For all codes considered in this study except 1999 SBC, the seismic response coefficient, C_s, based on the response spectrum procedure, is determined as

$$C_s = \frac{S_a}{R} \tag{1}$$

where S_a is the design spectral response acceleration at the fundamental period of the building, *T*, and *R* is the response modification factor. Note that we neglected the occupancy importance factor in Eq. 1, since all buildings in the portfolio are non-essential buildings whose occupancy importance factors are 1.

For 1999 SBC, the seismic design coefficient, which is equivalent to the seismic response coefficient, is determined as

$$C_s = \frac{1.2 A_v S}{R T^{2/3}} \tag{2}$$

where A_v is the seismic coefficient representing the effective peak velocity-related acceleration, and S is the coefficient for the soil profile characteristic of the site. Alternatively, the seismic design coefficient need not be greater than the following equation:

$$C_s = \frac{2.5 A_a}{R} \tag{3}$$

where A_a is the seismic coefficient representing the effective peak acceleration. In the derivation of a vulnerability model for each building, the seismic response or design coefficient is used to construct the capacity curve of the building, which will be explained in detail later.

Determination of Seismic Design or Performance Category

By all codes except 1999 SBC, the seismic design category is determined based on the seismic use group and the design spectral response acceleration parameters, S_{DS}, and S_{D1}. In case of 1999 SBC, seismic performance category, which is equivalent to the seismic design category, is determined based on the effective peak velocity-related acceleration, A_v, and the seismic hazard exposure group. Note that all buildings in the portfolio are assigned to seismic use or hazard exposure group I, since they are non-essential buildings. In the derivation of a vulnerability model for each building, the seismic design or performance category is used to determine damage state thresholds, which will be explained in detail later.

Seismic Design Ground Motions

Each seismic design code has its own seismic design map used for displaying and determining design ground motion values. The following is a short description of the source and level of design ground motion values in each design code: 2009 NEHRP Provisions provides risk-targeted ground motion based on 2008 USGS NSHM (Petersen et al., 2008), which is expected to have a building collapse probability of 1% in 50 years (Luco et al., 2007). The probabilistic portions of the seismic design maps in 2006 IBC and 2003 IBC provide ground motion values from 2002 USGS NSHM (Frankel et al., 2002) and 1996 USGS NSHM (Frankel et al., 1996), respectively, that have a 2% probability of exceedance in 50 years. The amended 2003 IBC provides 1.5 times ground motion values that have a 10% probability of exceedance in 50 years from 1996 USGS NSHM (Frankel et al., 1996). The 1999 SBC is based on ATC 3-06 (1978), which provides design ground motion values that approximately have a 10% probability of exceedance in 50 years.

Below are the procedures to determine the design spectral response acceleration or seismic coefficient. By all codes except 1999 SBC, the design spectral response acceleration, S_a is determined as follows: 1) S_s and S_1, the spectral response accelerations at 0.2 sec and 1.0 sec, respectively, are determined from the seismic design maps. 2) S_{DS} and S_{D1}, the design spectral response acceleration parameters at 0.2 sec, and 1.0 sec, respectively, are determined as

$$S_{DS} = \frac{2}{3} F_a S_s, \text{ and } S_{D1} = \frac{2}{3} F_v S_1 \tag{4}$$

where F_a and F_v are short and long-period site coefficients, respectively. 3) S_a is determined using a design response spectrum which is hinged on the design spectral response acceleration parameters, S_{DS} and S_{D1}. By 1999 SBC, the seismic coefficients, A_v and A_a are determined from the seismic ground acceleration maps.

Figure 3 shows the box plots of design spectral response accelerations at 0.2 sec (S_{DS}) and 1.0 sec (S_{D1}), respectively, in the study area for the five seismic design codes. Note that $2.5A_a$ and A_vS was used as proxies of S_{DS} and S_{D1}, respectively, for the 1999 SBC. The design spectral response accelerations for amended 2003 IBC are even lower than the previous code used I nthe region, i.e. 1999 SBC.

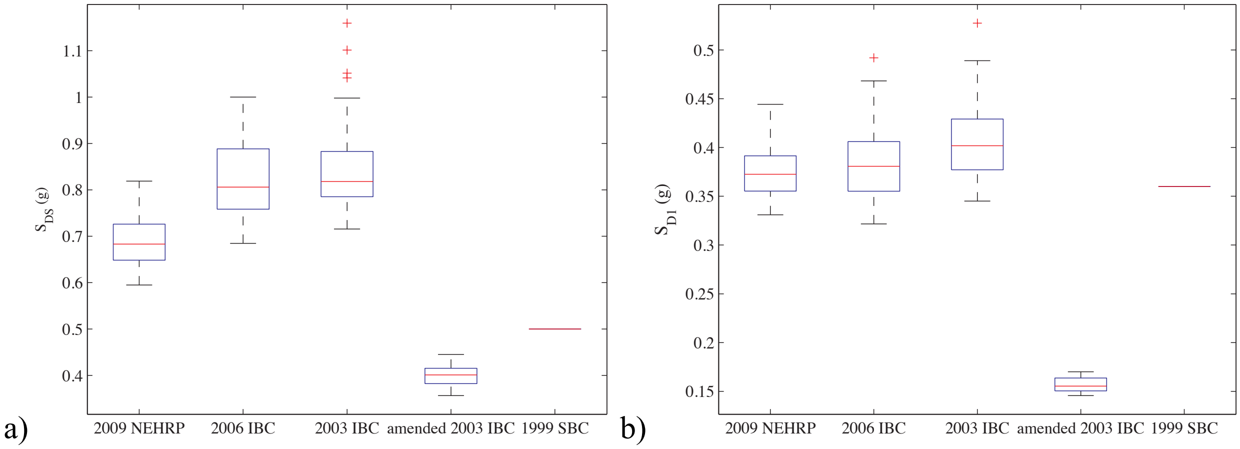

Figure 3. Box plots of design spectral response accelerations at 0.2 and 1.0 sec, respectively, for the five seismic design codes

Building Fragility and Vulnerability

Building fragility curves relate ground motion intensity (e.g., spectral acceleration) to the probability of exceeding various building damage states or performance levels. Building vulnerability curves relate ground motion intensity to the expected loss in value due to structural or non-structural damage. In this study, we developed the fragility and vulnerability models based on the methodology proposed in Karaca and Luco (2008; 2009). In the methodology of Karaca and Luco (2008), building response was estimated by time history analysis of single degree of freedom systems corresponding to the HAZUS capacity (or pushover) curves under a large number of earthquake records, instead of the capacity spectrum method applied in HAZUS.

For each building designed according to one of code options, we constructed the building capacity curve using the estimated C_s, and T along with other HAZUS parameter values such as ductility factor, μ, which were determined based on the building type and the design code level. For example, Figure 4a) shows the constructed capacity curves for steel light frame buildings (S3) designed according to the seismic code options. The estimated Cs values for the buildings were 0.14, 0.17, 0.17, 0.08, and 0.1, in the order of the code options, and the assigned design code levels are all high-code, except moderate-code by the amended 2003 IBC. Note that we assumed that the seismic design or performance category D or E corresponds to the high-code in HAZUS, and C corresponds to the moderate-code in HAZUS.

We also determined median and the lognormal standard deviation of the damage state thresholds by taking HAZUS values corresponding to the building type and the code level. For the S3 building, the median damage state thresholds of complete damage states for structural component are 9.45 (high-code) and 7.09 inches (moderate-code), respectively. We then derived the fragility curves by coupling the damage state thresholds along with statistics of the building response. We used the same procedure to derive the fragilities for both structural and non-structural components. We finally derived vulnerability curves by using the derived fragility curves for structural, and nonstructural components (for a given building type) along with the damage/loss ratios (for a given occupancy class) provided in HAZUS. Figure 4b shows the resulting vulnerability curves for the S3 building whose occupancy class is wholesale trade (COM2), for the design alternatives. When the building was designed according to the amended 2003 IBC, it was designed with the lowest Cs resulting in a seismic design class of C and hence assigned to the moderate-code level; as a result it had the highest vulnerability compared to designs based on other design codes. Note that the derived fragility and vulnerability models can be directly combined with available seismic hazard data such as the Memphis urban hazard curve, since they are all conditioned on spectral accelerations.

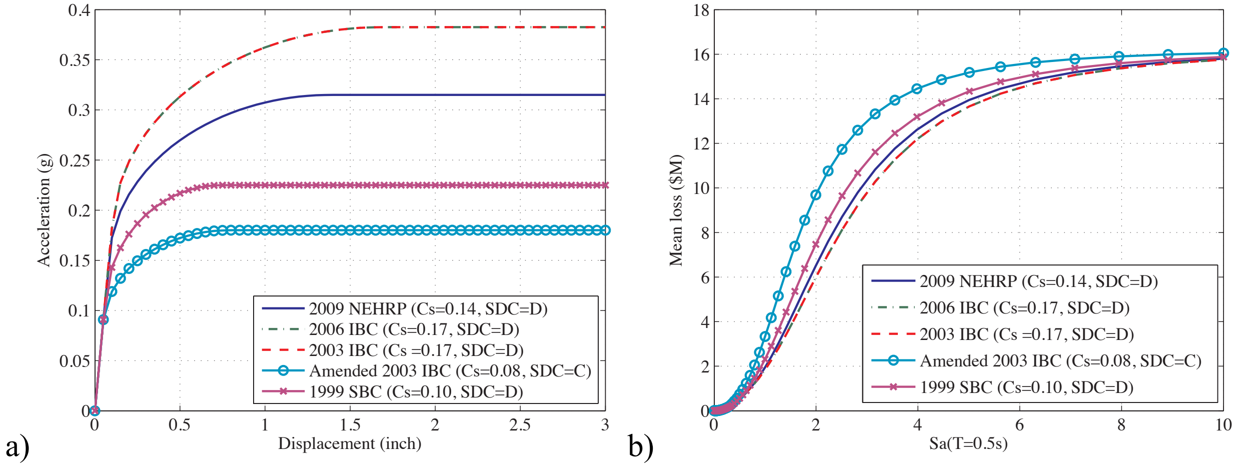

Figure 4 Derivation of vulnerability models. Panel a) shows the capacity curves for the S3 building, and panel b) shows the vulnerability curves for the S3 building whose occupancy class is wholesale trade (COM2) for the building code options.

Computation of Expected Annual Loss

For each building, the expected annual loss (EAL) is computed by coupling the vulnerability and the hazard curve at the building's location as

$$EAL = \int E\left[L \mid GM = a\right] \left| \frac{\mathrm{d}H_{GM}(a)}{\mathrm{d}a} \right| \mathrm{d}a \qquad (5)$$

where $E\left[L \mid GM\right]$ is the vulnerability curve for a given building designed to one of design alternatives, and H_{GM} is the hazard curve at the location of the building. The total expected annual loss for the portfolio buildings designed based on one of design alternatives is simply computed by taking the sum of expected losses across the buildings in the portfolio. Figure 5a) shows the normalized total expected annual losses for the building portfolio across seismic design options. We normalized them by the total expected annual loss for design based on the 2009 NEHRP, i.e. US$ 0.87M for the Memphis urban hazard and US$ 0.78M for the adjusted US hazard. The effect of different hazard curves on calculated expected losses was less than the effect of different design code options.

In addition to above annual expected loss calculations through use of hazard curves, we may compute the expected loss due to a scenario earthquake deterministically using grid data of expected ground motion intensities for the earthquake event. We compute the expected losses due to two scenario earthquakes (M7.7 and M6.2) (http://earthquake.usgs.gov/regional/ceus/products/grid_download.php). Figure 5b) shows the total expected losses for two scenario earthquakes (M7.7 and M6.2), which are also normalized by the total expected loss for design based on the 2009 NEHRP. The total expected loss to the portfolio for design based on the 2009 NEHRP are US$ 193.53M and US$ 13.40M due to the M7.7 and M6.2 scenario earthquakes, respectively. In case of the M7.7 scenario earthquake, we observe a larger difference between maximum and minimum losses, compared to the case of the M6.2 scenario earthquake, since vulnerability curves have relatively similar values in lower range of ground motion intensities resulting in similar losses as seen in Figure 4b).

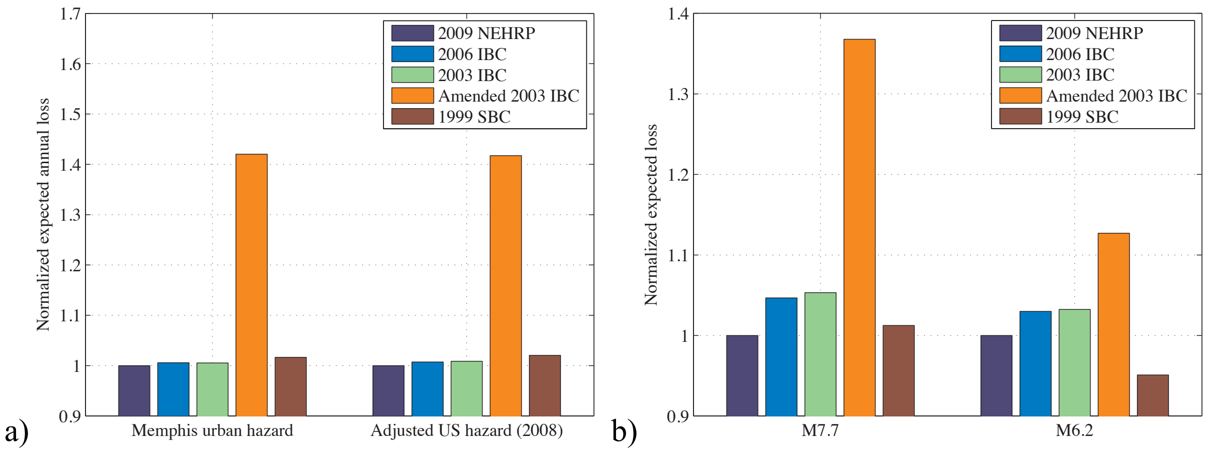

Figure 5. Risk assessment results. Panel a) shows the normalized total expected annual losses for seismic design alternatives coupling with either Memphis urban hazard curves or adjusted US hazard curves. Panel b) shows the normalized total expected losses due to two scenario earthquakes.

Discussions

From the risk assessment results, we observe that the portfolio of simulated buildings experienced largest losses when they were designed according to the amended 2003 IBC since the design spectral response accelerations (Figure 3) by the amended 2003 IBC are much lower than others, which resulted in lower C_s, higher vulnerability, and finally larger loss to the buildings designed according to the amended 2003 IBC.

However, the slight difference of the design response accelerations between the amended 2003 IBC and the 1999 SBC alone cannot explain the large difference of losses between them. As described in the previous section, all buildings designed according to the amended 2003 IBC were assigned to a seismic design class of C and hence the moderate-code level in HAZUS framework, whereas they were assigned to the high-code level as they were designed according to the 1999 SBC. In the methodology of Karaca and Luco (2008), the damage state thresholds are determined based on the design code level regardless how large or small the C_s which building was designed with. If all buildings designed according to 2003 IBC amended are fictitiously assigned to the high-code, then the total expected annual loss decreases to US$ 0.96M from US$ 1.24M. Similarly, if all buildings designed according to 1999 SBC are fictitiously assigned to the moderate-code, then the total expected annual loss increases to US$ 1.16M from US$ 0.88M.

We also found that lower C_s did not always result in higher expected (annual) loss, as shown in Figure 6a, which shows the relationship between Cs and expected annual loss for a wood light frame building (labeled W1 in HAZUS) whose occupancy class is retail trade (labeled COM1 in HAZUS). The reason is 1) the expected annual loss is dominated by the vulnerability at the lower intensity levels, 2) at the lower intensity levels, the vulnerability is dominated by the fragility for non-acceleration components and 3) The building designed with higher Cs value has larger fragility for non-structural acceleration-sensitive component, but lower fragilities for structural and non-structural drift-sensitive components.

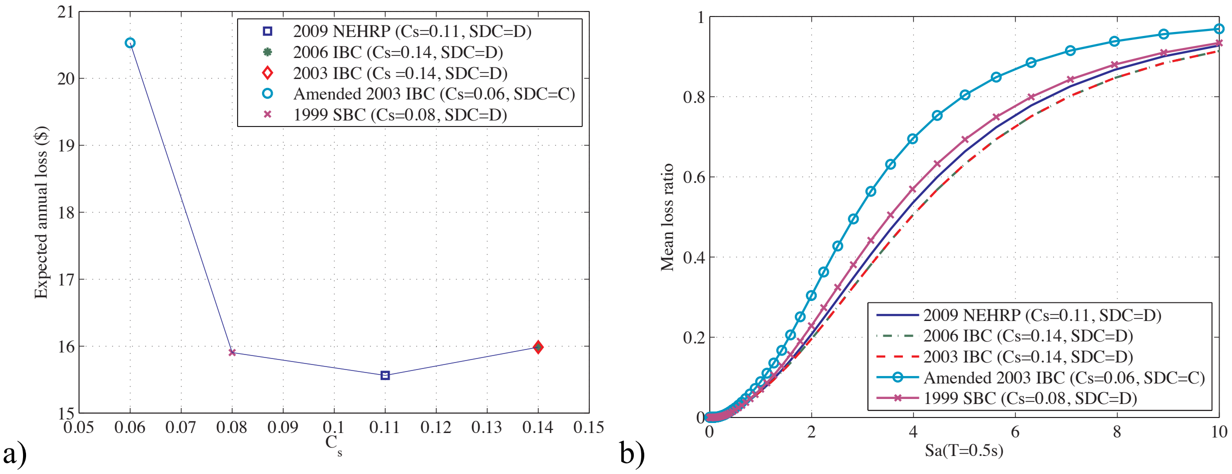

Figure 6. a) Expected annual loss vs. Cs, and b) expected loss vs. Cs for the five building code options

Conclusions

We performed a regional risk assessment study for Memphis in order to evaluate the implications of adopting five different seismic code options: 1) 2009 NEHRP Recommended Provisions, 2) 2006 IBC, 3) 2003 IBC, 4) amended 2003 IBC, and 5) 1999 SBC. The results illustrate that expected annual losses and expected losses for scenario events are significantly higher for design based on the amended 2003 IBC compared to the other design options. The higher risk for design based on the amended 2003 IBC was due to the lower design spectral response accelerations, which resulted in lower Cs, and lower seismic design category. Especially, the lower seismic design category had a large effect on the higher risk for design based on the amended 2003 IBC. From the risk assessment results, the amendment to the 2003 IBC allowing the use of alternative ground motion for design of non-essential buildings induced higher risk than other options, even higher than the 1999 SBC.

Acknowledgments

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References

FEMA, 2003. *HAZUS-MH MR-1 Technical Manual*, Federal Emergency Management Agency, Washington, D.C.

Gomberg, J., and E. Schweig, 2002. Earthquake Hazard in the Heart of the Homeland, *U.S. Geological Survey Factsheet FS-131-02.*

Karaca, E., and N. Luco, 2008. Development of hazard-compatible building fragility and vulnerability models, *Proc. of the 14th World Conference on Earthquake Engineering*, Beijing, China.

Karaca, E., and N. Luco, 2009. Development of seismic hazard compatible building fragility functions: Application to HAZUS building types, submitted for Earthquake Spectra.

Cramer, C. H., J. S. Gomberg, E. S. Schweig, B. A. Waldron, and K. Tucker, 2004. The Memphis, Shelby County, Tennessee, Seismic Hazard Maps, *USGS Open File Report 2004-1294*.

Luco, N., B. Ellingwood, R. O. Hamburger, J. D. Hooper, J. K. Kimball, and C. A. Kircher, 2007. Risk-targeted vs. current seismic design maps for the coterminous United States, *Proc., Annual SEAOC 2007 Conference*, Structural Engineers Association of California.

Petersen, M. D., A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills, and K. S. Rukstales, 2008. Documentation for the 2008 Update of the United States National Seismic Hazard Maps, *U.S Geological Survey Open File Report 2008-1128*.

Frankel, A. D., M. D. Petersen, C. S. Mueller, K. M. Haller, R. L. Wheeler, E. V. Leyendecker, R. L. Wesson, S. C. Harmsen, C. H. Cramer, D. M. Perkins, and K. S. Rukstales, 2002. Documentation for the 2002 Update of the National Seismic Hazard Maps, *U.S Geological Survey Open File Report 02-420.*

Frankel, A. D., C. S. Mueller, T. Barnhard, D. M. Perkins, E. V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper, 1996. National Seismic Hazard Maps, June 1996: Documentation, *U.S Geological Survey Open File Report 96-532.*

Applied Technology Council, 1978. *Tentative Provisions for the Development of Seismic Regulations for Buildings*, ATC Publication ATC 3-06, NBS Special Publication 510, NSF Publication 78-8, U. S. Government Printing Office, Washington, D.C.

Ryu, H., N. Luco, J. W. Baker, and E. Karaca, 2008. Converting HAZUS Capacity Curves to Seismic Hazard-Compatible Building Fragility Functions: Effect of Hysteretic Models, *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China.

Ryu, H., N. Luco, J. W. Baker, and E. Karaca, 2009. Capacity-Consistent Damage State Thresholds for HAZUS Model Building Types, in preparation.