11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 1298. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

FRAGILITY OF MEMPHIS BUILDINGS

J.-R. HUO and H. HWANG

Center for Earthquake Research and Information, The University of Memphis
Memphis, TN 38152, USA

ABSTRACT

This paper presents the fragility analysis methods for buildings in the Memphis area. The fragility analysis is one of the major tasks of the NCEER Loss Assessment of Memphis Buildings (LAMB) Project, which is a coordinated program that combines talents from structural engineering, seismology, risk/reliability, and socioeconomic researchers. The effort provides a demonstration of how these various disciplines can be integrated to estimate economic losses for a scenario earthquake in the Memphis area. In the paper, the fragility analysis of a typical low-rise RC shear wall building is described in detail to illustrate the fragility analysis methodology used in the LAMB project.

KEYWORDS

Damage states, earthquake, fragility, probability, loss, assessment, buildings, Memphis, urban.

INTRODUCTION

A large earthquake may cause damage to buildings and other facilities. As a consequence, it may cause death/injury to persons and induce direct/indirect economic losses to society. To improve the methodology for estimating seismic losses in an urban area, the National Center for Earthquake Engineering Research (NCEER) has initiated a research project entitled "Loss Assessment of Memphis Buildings (LAMB)." The LAMB project is a coordinated research program that combines the talents from structural engineering, seismology, risk/reliability, and socioeconomic researchers. The effort provides a demonstration of how these various disciplines can be integrated to estimate economic losses in an urban area resulting from a scenario earthquake.

One of the critical tasks of a seismic loss study is to assess the vulnerability of existing buildings in the event of an earthquake. The likelihood of damage to buildings caused by various levels of ground shaking is usually expressed in terms of fragility curves or damage probability matrices. In this paper, we present the methods for fragility analysis of buildings in the Memphis area. The results from fragility analysis will be used to demonstrate the methodology for estimating seismic losses in the Memphis area.

NCEER EFFORT ON FRAGILITY ANALYSIS

The fragility analysis of buildings in the Memphis area is coordinated by Shinozuka of the University of Southern California. On the basis of building inventory collected by Jones and Malik (1996), three types of buildings are considered: unreinforced masonry (URM) buildings, reinforced concrete (RC) shear wall buildings, and RC frame buildings with infill masonry walls. The fragility analysis of URM buildings is performed by Wen and Abrams of the University of Illinois at Urbana-Champaign, the fragility analysis of RC frames with infill walls is carried out by White of Cornell University and Hwang and Huo of the University of Memphis, and the fragility analysis of RC shear wall buildings is performed by Huo and Hwang of the University of Memphis.

In these fragility analyses, an analytical model for each type of building is established by calibrating with experimental results (Costley and Abrams, 1996; Kunnath *et al.*, 1996; Mosalam *et al.*, 1996). Synthetic ground acceleration time histories corresponding to various levels of ground shaking intensities are generated with a seismologically based model, in which the effect of seismic source, path attenuation, and local soil conditions on ground motion is taken into account (Hwang and Huo, 1994b; Horton *et al.*, 1996). From nonlinear seismic response analyses, probabilistic seismic responses of buildings corresponding to various levels of ground shaking are determined. On the other hand, several damage states of buildings are established based on earthquake experience data and experimental data. Finally, seismic reliability analyses are performed to determine the damage probabilities of the building subject to various levels of ground motions and the results are displayed as fragility curves or damage probability matrices. In the following section, a fragility analysis of a typical low-rise RC shear wall building is presented to illustrate the fragility analysis methodology.

FRAGILITY ANALYSIS OF A LOW-RISE RC SHEAR WALL BUILDING

Generation of Ground Motion

The seismic hazards in the Memphis area are from the New Madrid seismic zone (NMSZ) where three of the largest earthquakes in the history of the United States occurred in the winter of 1811-1812. Since strong earthquake motion data in the NMSZ are scarce, the synthetic ground acceleration time histories generated by Hwang and Huo (1994b) are used. In their approach, a probabilistic seismic hazard analysis of the study area is first performed and the hazard-consistent magnitudes and distances are determined. For each pair of magnitude and distance, synthetic acceleration time histories at the base of a soil profile are generated using a seismologically based model, and then the nonlinear soil response analyses are performed to determine the acceleration time histories at the ground surface. Figure 1 shows the samples of earthquake acceleration time histories at the ground surface corresponding to various levels of peak ground acceleration (PGA). It is noted that these ground motions have different spectral contents and duration.

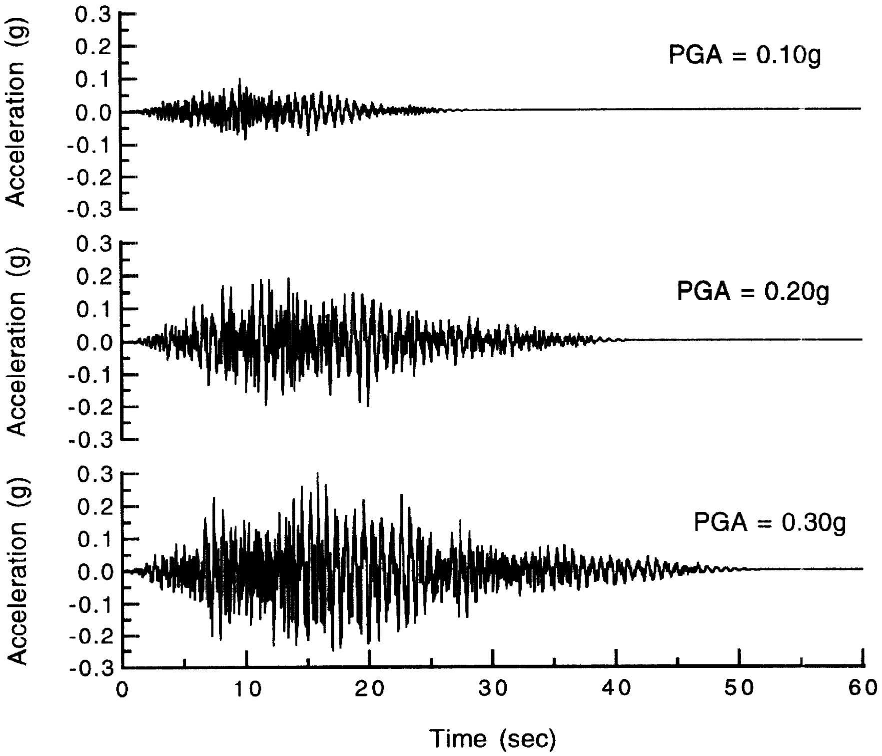

Fig. 1. Samples of earthquake acceleration time histories

Modeling of Building

In this study, Patterson Hall, a four-story RC shear wall building on the main campus of the University of Memphis, has been selected as a typical low-rise RC shear wall building in the Memphis area. The model of a typical floor plan is shown in Figure 2 and the story height of the building is 12 feet. The building was designed in 1966 without consideration of earthquake resistance, and the shear walls around two stairs are considered as the only seismic resistant system of the building. The shear walls are 12 inches thick through out the height of the building. The horizontal and vertical reinforcement is two layers of No. 4 steel bars with a spacing of 12 and 18 inches, respectively. Grade 60 reinforcement and concrete with a specified compressive strength of 3000 psi are used in the walls.

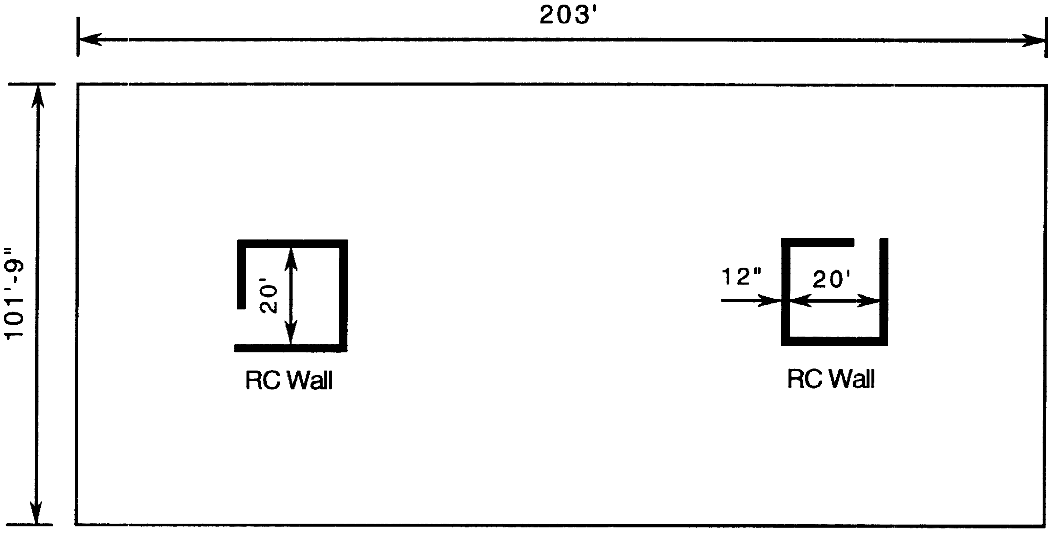

Fig. 2. Model of a typical floor plan of the building

Inelastic Behavior of RC Shear Wall

The computer program IDARC (Kunnath *et al.*, 1992) is used to determine the seismic response of the building. In the IDARC program, inelastic flexural and shear behavior of RC shear walls is simulated using a trilinear skeleton curve and four model parameters (α, β_D, β_E, and γ). The trilinear skeleton curve is governed by the cracking point, yielding point, initial stiffness, and post-yielding stiffness ratio. These quantities can be determined from member properties such as dimensions and reinforcement.

The parameter α is used for modeling stiffness degrading, β_D for ductility-controlled strength deterioration, β_E for hysteretic energy-controlled strength deterioration, and γ for pinching effect. In the hysteretic model for both flexural and shear behavior, a moderate degradation of stiffness is considered when the shear walls behave in the nonlinear manner. Thus, the stiffness degrading parameter α is taken as 2. Since no significant deterioration of strength is expected, the strength deterioration parameters β_D and β_E are taken as 0.1. Little pinching phenomenon is expected in the flexural behavior and the pinching parameter γ for flexure is thus taken as 1.0. On the other hand, the pinching is expected to be significant in the shear behavior and the pinching parameter γ for shear is taken as 0.3.

To perform a seismic response analysis using IDARC, a static analysis is first carried out and the result is then used as the initial condition for a dynamic analysis in which the Newmark-β algorithm is used in the time domain to solve the equations of motion. During each step of the dynamic analysis, the force, deformation, total absorbed energy, and dissipated hysteretic energy of each member are calculated. The maximum story response such as the maximum story displacement and the final damage pattern of the structure are determined at the end of the analysis.

Uncertainties in Seismic and Structural Parameters

In this study, uncertainties in the earthquake-site-structure system are quantified following the work by

Hwang and Huo (1994a) and Huo and Hwang (1995). The parameters modeling seismic source and path attenuation and their uncertainties are summarized in Table 1. The soil parameters considered as random variables are the low strain shear modulus, shear modulus ratio and damping ratio of soils. The shear modulus reduction curves and damping ratio curves for sand and clay are shown in Figures 3 and 4, respectively. The uncertainties in structural viscous damping ratio, strength and stiffness of construction materials are quantified and the uncertainties in these structural parameters are summarized in Table 2.

Table 1. Uncertainties in seismic parameters

Parameters	Distributions	Mean	Range
Stress parameter, $\Delta\sigma$	Uniform	150 bars	100 - 200 bars
High-cut frequency, f_m	Uniform	30 Hz	20 - 40 Hz
Radiation coefficient, $<R_{\theta\phi}>$	Uniform	0.56	0.48 - 0.64
Focal depth, H	Uniform	10 km	6 - 15 km
Phase angle, ϕ	Uniform	π	0 - 2π
Envelope function parameter, C_3	Uniform	0.5	0 - 1
γ_0 in quality factor $Q(f) = \frac{\pi}{\beta\gamma_0} f^{\eta}$	Uniform	0.0007	0.0006 - 0.0008
η in quality factor $Q(f) = \frac{\pi}{\beta\gamma_0} f^{\eta}$	Uniform	0.40	0.25 - 0.55
Strong motion duration, T_e	Lognormal	f(M, R)	COV = 0.35

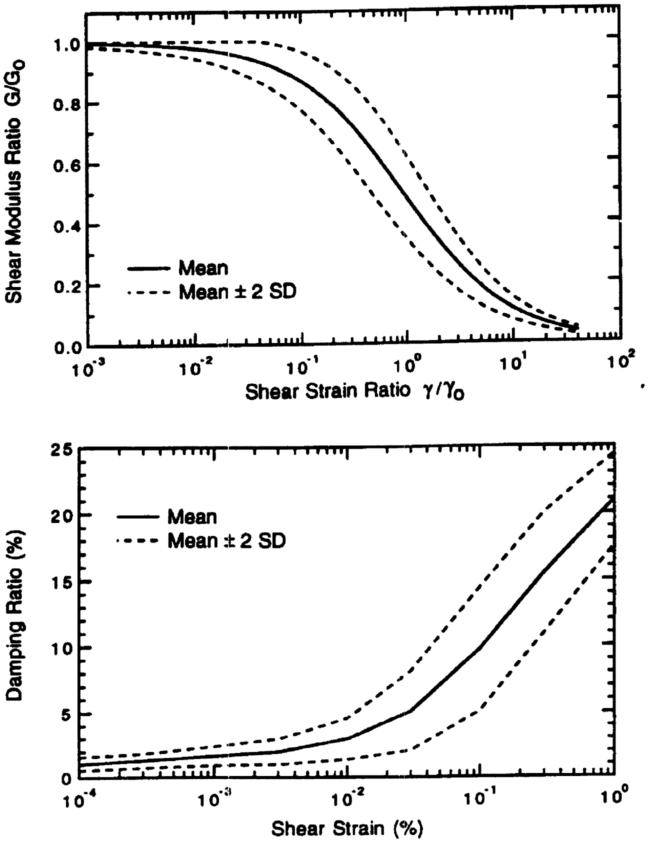

Fig. 3. Shear modulus reduction and damping ratio curves for sands

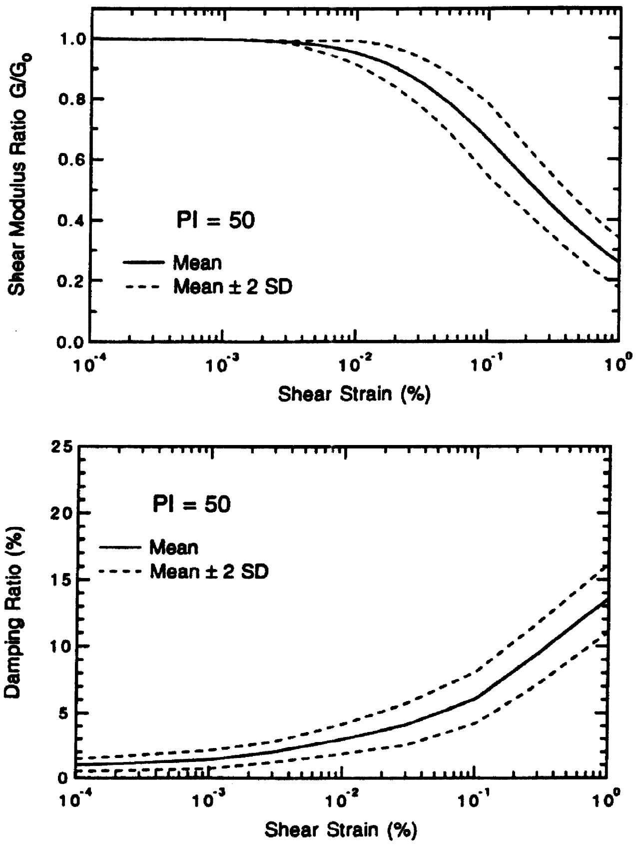

Fig. 4. Shear modulus reduction and damping ratio curves for clay with PI=50

Table 2. Uncertainties in structural parameters

Parameter	Distribution	Mean	Range
Concrete compressive strength	Normal	4297 psi	COV = 0.15
Concrete strain at maximum compressive stress	Uniform	0.02	0.015 - 0.025
Ultimate concrete strain	Uniform	0.04	0.03 - 0.05
Steel yield strength	Lognormal	71 ksi	COV = 0.11
Viscous damping ratio	Uniform	0.03	0.02 - 0.04

Probabilistic Seismic Response

For each random parameter, 50 samples are randomly generated. These samples are then combined using the Latin Hypercube sampling technique (Iman and Conover, 1980) to generate 50 samples of the earthquake-site-structure system. For a given level of PGA, each sample of the earthquake-site-structure system is analyzed using the IDARC program to determine the nonlinear seismic response of structure such as the floor acceleration, member forces, and story displacement. In general, structural damage due to earthquakes can be attributed to excessive deformation. The story drift ratio which is derived from structural displacement is a good measure of structural damage. In this study, the damage states of shear wall buildings are defined using the maximum story drift ratio. For the structure selected in this study, the flexural behavior of the shear wall is dominant and the maximum story drift ratio occurs in the first story. These results are consistent with the test of RC shear walls by Vallenas *et al.* (1979). In this study, the maximum story drift ratio is taken to be lognormally distributed and the statistics corresponding to various PGA levels are shown in Table 3.

Table 3. Statistics of maximum story drift ratio

PGA (g)	Maximum story drift ratio, δ (%)			
	Mean	COV	Median	β
0.05	0.02	0.30	0.02	0.29
0.10	0.15	0.56	0.13	0.52
0.15	0.26	0.35	0.25	0.34
0.20	0.38	0.35	0.36	0.34
0.25	0.46	0.34	0.44	0.33
0.30	0.62	0.54	0.55	0.51
0.40	0.93	0.46	0.84	0.44
0.50	1.62	0.62	1.38	0.57

Damage States

As indicated in Table 4, four damage states are considered: (1) no damage, (2) insignificant damage, (3) moderate damage, and (4) heavy damage (Eguchi and Chang, 1996). Aktan and Bertero (1985) summarized the experimental results of RC shear walls at the University of California at Berkeley. In the tests under cycling loads, the hairline cracks are usually observed starting at the maximum story drift ratio δ of approximately 0.2%. Thus, the boundary between no damage and insignificant damage is taken as 0.2%. Aktan and Bertero (1985) reported that the wall specimens yield at a story drift ratio of 0.44% on average, and then the longitudinal steels start to yield and the flexural cracks are developed in the wall panels (Vallenas *et al.*, 1979). The average value of δ of 0.4% at yielding was also reported by Aoyama (1981) from the tests of RC shear walls in Japan. From these data, the boundary between insignificant damage and moderate damage is taken as 0.5%. Vallenas *et al.* (1979) indicated that at δ of 0.88%-1.32%, the concrete cover in the compression region of the specimen starts to spall and the extensive flexural-shear cracks occur in the tensile region. These factors show the wall specimens severely damaged. Therefore, the low bound value of δ for heavy damage is determined as 1.0% in this study. The ranges of story drift ratio corresponding to various damage states are summarized in Table 4.

Table 4. Damage states

Damage state	Extent of damage	Response level	Story drift ratio (%)
No damage	There is no damage visible in either cosmetic or structure elements.	Elastic	< 0.2
Insignificant damage	Damage requires no more than cosmetic repair. No structural repairs are necessary.	Cracking	0.2 - 0.5
Moderate damage	Repairable structural damage has occurred. The existing elements can be repaired essentially in place, without substantial demolition or replacement of elements.	Yielding	0.5 - 1.0
Heavy damage	Damage is so extensive that repair of elements is either not feasible or requires major demolition or replacement.	General yielding	> 1.0

Fragility Curves

The structural fragility with respect to a damage state is defined as the probability that the structural response exceeds the structural capacity defined by the damage state. In this study, both structural response and structural capacity are expressed in terms of maximum story drift ratio δ. The probability PF_{ij} that the damage exceeds the *i*th damage state given the occurrence of an earthquake with PGA equal to A_j can be determined as

$$PF_{ij} = \text{Prob}(\delta \geq \delta_i \mid PGA = A_j) \tag{1}$$

where δ is the maximum story drift ratio resulting from an earthquake with the PGA equal to A_j, δ_i is the low bound of the story drift ratio for the *i*th damage state. The fragility curve with respect to the *i*th damage state can be then constructed using the PF_{ij} values at various PGA levels. Figure 5 shows the fragility curves for the typical low-rise RC shear wall buildings in the Memphis area.

The damage probability matrix describes the probability of damage in various damage states caused by an earthquake. The probability of damage in the *i*th damage state PDS_{ij} given the occurrence of an earthquake with PGA equal to A_j can be derived from the fragility data

$$PDS_{ij} = \begin{cases} PF_{ij} - PF_{i+1j} & (i \leq 4) \\ PF_{ij} & (i = 5) \end{cases} \tag{2}$$

On the basis of fragility data shown in Figure 5, the damage probability matrix for the typical low-rise RC shear wall buildings in the Memphis area is established and shown in Table 5.

CONCLUSIONS

This paper presents the methods for fragility analysis of buildings in the Memphis area. Particularly, the fragility analysis of a low-rise RC shear wall building is described in detail. In the fragility analysis, the ground motion is generated using a seismologically based model. In addition, the effect of local soil conditions on ground motion is included through nonlinear site response analysis. Furthermore, an appropriate model for the building is established and nonlinear behavior of the buildings is incorporated in the fragility analysis. The effects of uncertainties in seismic source, path attenuation, local soil condition, and nonlinear building behavior on fragility of buildings are considered systematically. Thus, the methodology of fragility analysis of buildings has been improved in this study.

As mentioned in the introduction, the work described in this paper is part of the LAMB project. The fragility curves and damage probability matrix resulting from this study will be used to demonstrate the methodology for estimating seismic losses in the Memphis area.

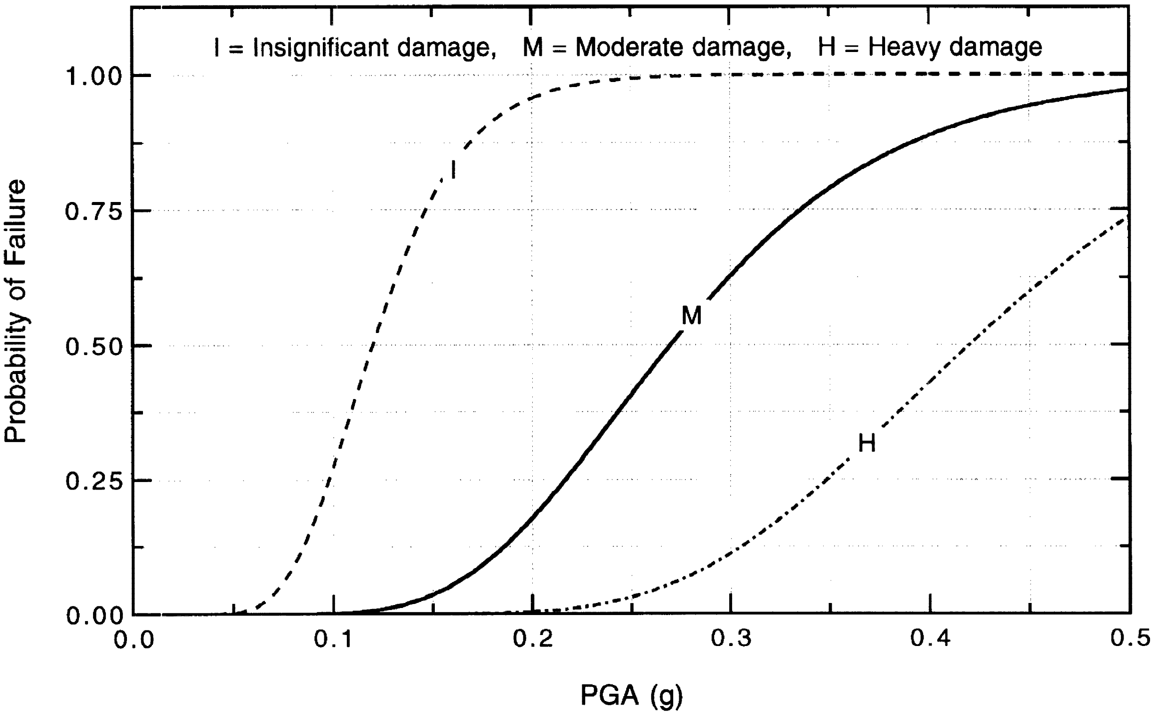

Fig. 5. Fragility curves of a typical low-rise RC shear wall building in the Memphis area

Table 5. Damage probability matrix

PGA (g)	No damage	Insignificant damage	Moderate damage	Heavy damage
0.05	1.00	0.00	0.00	0.00
0.10	0.71	0.28	0.01	0.00
0.15	0.22	0.75	0.03	0.00
0.20	0.03	0.76	0.21	0.00
0.25	0.01	0.59	0.39	0.01
0.30	0.01	0.32	0.49	0.18
0.40	0.00	0.08	0.49	0.43
0.50	0.00	0.02	0.18	0.80

ACKNOWLEDGMENTS

This paper is based on research supported by the National Center for Earthquake Engineering Research under contract numbers NCEER 944102B (NSF Grant No. BCS-9025010). Any opinions, findings, and

conclusions expressed in the paper are those of the writers and do not necessarily reflect the views of the NCEER, or the NSF of the United States.

REFERENCES

Aktan, A.M. and V.V. Bertero (1985). RC structural walls: seismic design for shear. *Journal of Structural Engineering, ASCE,* **111**(8), 1775-1791.

Costley, A.C. and D. Abrams (1996). Dynamic response of sample masonry buildings in Memphis. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Eguchi, R. and S. Chang (1996). Losses associated with building damage in Memphis. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Horton, S.P., N. Barstow, and K. Jacob (1996). Simulation of strong ground motion in Memphis. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Huo, J.-R. and H. Hwang (1995), Seismic fragility analysis of buildings in Memphis. *Technical Report*, Center for Earthquake Research and Information, the University of Memphis, Memphis, TN.

Hwang, H. and J.-R. Huo (1994a). Generation of hazard-consistent fragility curves. *International Journal of Soil Dynamics and Earthquake Engineering*, **13**(5), 345-354.

Hwang, H. and J.-R. Huo (1994b). Generation of hazard-consistent ground motions. *International Journal of Soil Dynamics and Earthquake Engineering*, **13**(6), 377-386.

Iman, R.L. and W.J. Conover (1980). Small sample sensitivity analysis techniques for computer models, with an application to risk assessment. *Communications in Statistics*, **A9**(17), 1749-1842.

Jones, B. and A. Malik (1996). The building stock in Memphis: Relating structural type and use. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Kunnath, S.K., A.M. Reinhorn, and R. Mattox (1996). Evaluation of seismic damageability for typical R/C buildings in Memphis. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Kunnath, S.K., A.M. Reinhorn, and R.F. Lobo (1992). IDARC version 3.0: A program for the inelastic damage analysis of reinforced concrete frame-wall structures. *Technical Report NCEER-92-0022*, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, New York.

Mosalam, K.M., P. Gergeley, and R.M. White (1996). Effect of geometrical configuration on the seismic response of infilled frames. *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, June 23-28, 1996.

Vallenas, J.M., V.V. Bertero, and E.P. Popov (1979). Hysteretic behavior of reinforced concrete structural walls. *Report No. UCB/EERC-79/20*, University of California, Berkeley, CA.