1993 NATIONAL EARTHQUAKE CONFERENCE
Earthquake Hazard Reduction in the Central and Eastern United States:
A Time for Examination and Action

HEIGHTENING HAZARD AWARENESS USING SIMPLE STRUCTURAL MODELS IN REAL AND VIRTUAL ENVIRONMENTS

Kenyon D. Potter[1]

ABSTRACT

Heightening awareness to earthquake hazards requires the use of diverse educational approaches. The appropriateness of a particular approach depends on the intended audience. Techniques used to educate an audience of corporate professionals, building owners, and the general public, may differ from those used with engineering professionals. This paper examines an approach based on the demonstration of earthquake hazards. Demonstrations can be performed in the real environment using physical models or in a virtual environment using computer models. The development and use of a portable demonstration system is reported. The system uses simple physical models of structures to illustrate selected earthquake hazards. Five models are assembled from pre-fabricated building elements. Each model represents a structure with a different lateral force resisting system (LFRS). A series of demonstrations is described which illustrate hazards related to interaction of different LFRS. An alternative system is proposed using computer models. The purpose of these demonstrations is to increase the audience's knowledge of potential earthquake hazards. It is believed that a more knowledgeable audience results in heightened awareness.

INTRODUCTION

Earthquake hazard reduction in the Central and Eastern United States is in its infancy. Current engineering practice in these regions infrequently incorporates the use of earthquake-resistant design principles although many buildings have marginal earthquake resistance due to their engineering design for wind. Despite current practice, there are signs of progress. Earthquake conferences increasingly focus on earthquake hazard reduction. Principal

---

[1] Engineer, Advanced Engineering Consultants, Inc., San Francisco, CA 94104

metropolitan areas have undertaken efforts to codify their first seismic provisions for new construction as reported by [1,2]. However, many existing structures remain vulnerable due in part to pertinent parties lacking awareness of earthquake hazards.

The impetus for hazard reduction is driven by heightened awareness of corporate professionals, building owners, and the general public. In the western United States, notably California, awareness has been raised due to the damage resulting from the frequent recurrence of earthquakes and the ongoing activities of professionals in the field of earthquake engineering. In contrast, other regions remain much less aware despite the availability of published research. A significant problem is that the transfer of knowledge from researchers to practicing professionals and other pertinent parties faces many impediments which are summarized in [3]. While this problem is not fully addressed in this paper, the solution appears to reside in expanded efforts towards education. In a partial effort, practicing engineers who have knowledge of earthquake hazards could act as educators and lead efforts to raise awareness among corporate professionals and building contractors with whom they interact. Moreover, technical professionals in both research and practice could endeavor to heighten the awareness of the general public.

In engineering tradition, the textbook, journal article or conference proceeding represents the primary vehicles for education. The conventional presentation format is text, tables and 2-D graphics i.e. figures. While appropriate for presentation to an audience of technical professionals, the conventional format may not be suitable for audiences outside the engineering profession. Instead, educators may need to present earthquake hazard knowledge in formats more appealing to the intended audience. Multi-sensory demonstrations are attractive and can increase audience attentiveness. For example, when demonstrating to a non-technical corporate or government audience, an attractive presentation format may incorporate dynamic 3-D graphics with an acoustic accompaniment. Due to popular appeal, interactive demonstrations may be more suitable for educating student audiences and the general public.

Although 2-D visuals using hardcopy or projection techniques are currently the predominant educational medium, videotape and multi-media technologies have been used to produce documentaries and interactive programs which offer useful knowledge with respect to potential earthquake hazards as evidenced by [4,5,6,7]. While such efforts represent significant endeavors by leading corporate and government entities, the videos and multimedia programs have not addressed other important hazards such as those which arise due to structural configurations. To heighten awareness to specific hazards, other educational tools may be appropriate to demonstrate earthquake hazards. Physical models have long been used as a proven technique to demonstrate basic concepts in science and engineering. In addition, new educational technologies are emerging from scientific visualization to virtual reality. New computer applications make possible unprecedented learning opportunities. The unrestricted nature of models in a virtual environment permits the audience to experience a wealth of simulated events as described in [8].

This paper focuses on the development of a demonstration system to illustrate structural hazards due to severe ground shaking. The system uses physical models to perform multi-sensory demonstrations before varied audiences. In addition, an alternative system is proposed which uses computer models to perform multi-sensory demonstrations in a virtual environment. Both demonstrations are portable and permit operation in any setting. By use of either demonstration system, it is intended that the engineer-educator may increase the audience's knowledge of specific hazards and heighten general awareness.

DEMONSTRATION SYSTEMS

Background

Researchers of earthquake engineering often use scale models, which require permanent testing laboratories, to simulate responses of structures subject to ground shaking. In contrast, practicing engineers use finite element models to determine approximate structural responses. These conventional approaches generally focus on the independent behavior of a structural system. However, for a given structural configuration, other hazards related to the interaction of structures may need consideration. This paper presents a demonstration system and describes its operation to illustrate three selected hazards:

- pounding between adjacent structures;
- incompatible stiffness of structural elements; and
- out-of-plane instability of masonry.

A working knowledge of these and other structural hazards is essential for engineers practicing earthquake-resistant design. At the same time, it is important that other professionals and decision-makers in the design process have at least a conceptual knowledge of such hazards. The theoretical bases for hazards related to structural configuration are discussed in [9,10].

Demonstrations in the Real Environment

A prototype audio-visual demonstration system was developed to demonstrate hazards using physical models. The desktop system is portable and can be used in most settings to demonstrate potential structural hazards associated with severe ground shaking. The demonstration system has four main components: (1) a 1/16 hp DC motor; (2) a shaking platform; (3) a sound synthesizer; and (4) physical models. The demonstration system is depicted in Figure 1. Rotation of the eccentric mass induces harmonic oscillations in the platform. These oscillations simulate horizontal ground shaking. The motor has a variable control so that the input frequency can be tuned appropriately. In addition, the sound synthesizer is synchronized with the motor so that a tone sounds with each rotation of the motor. Hence, frequencies can be approximately identified without using an oscilloscope.

Five 3-D models of 1/36 scale are used to demonstrate hazards related to the lateral stiffness of structures. Models represent two-level structures of approximately equal height with varied lateral force resisting systems (LFRS) including a moment-resisting frame (MRF), concentric braced frame (CBF), eccentric-braced frame (EBF), masonry shear wall (MSW), and a concentric braced frame with masonry infill (CBF+MSW). Elevations of the models are shown in Figure 2. Due to similitude requirements, it is difficult to extract accurate structural responses from very small-scale models; however, for demonstration purposes, such models are satisfactory because many requirements may be relaxed according to [11]. Elements used in the models were selected by the three criteria: 1) models should not require extensive construction; 2) lateral deflections should be visible to the audience; and 3) the range of model frequencies should roughly match those of actual structures with the same LFRS. Table 1 lists the composition of each model. To minimize model preparation time, models are assembled from commercially-available, pre-fabricated building elements.

TABLE 1. Composition of models

Model	Prefabricated Building Elements		
	Beams & Columns	Walls	Bracing
A	Cellular foam sheet*	---	---
B	Erector Set® girders	---	extension springs
C	Erector Set® girders	---	extension springs
D	---	LEGO® bricks	---
E	Erector Set® girders	LEGO® bricks	extension springs

Erector Set® is an exclusive trademark of Meccano, SA. and LEGO® is an exclusive trademark of INTERLEGO, AG. Used with permission.

*Minimal fabrication required.

To insure visibility of lateral deflections, selected elements have significantly smaller stiffness parameters than actual building elements. Where a stiffness parameter is unknown, its value is estimated by measuring the end deflection of a cantilever due to a transverse force at the end. Due to the small stiffness parameters, the amount of added mass required to achieve desired model frequencies is minimized. Consequently, a small mass equivalent to 1.0 pound weight is lumped at each story level. Except for models utilizing brick elements, the model selfweight is disregarded. For each model, the fundamental frequency and the corresponding period are presented in Table 2. By inspection, the range of model frequencies sufficiently matches that of structures with the same LFRS to enable the making of instructive demonstrations.

A series of demonstrations is performed to simulate the three specific hazards described above. For a given demonstration, selected models are placed on the shaking platform in one of three orientations (side-by-side, end-to-end or perpendicular) as depicted in Figure 3. The series of demonstrations is outlined in subsequent paragraphs.

TABLE 2. Lateral stiffness and dynamic properties

Model	LFRS	Stiffness Parameter	f_{FUND} (Hz.)	T (sec.)
A	MRF	EI = 0.4 lb-in^2	0.5	2.0
B	CBF	AE = 2.5 lb	1.3	0.8
C	EBF	AE = 2.5 lb	1.2	0.8
D	MSW	AG = 188 lb	11.1	0.09
E	CBF+MSW	AG = 188 lb	11.1	0.09

To introduce the audience to model dynamics, a preliminary demonstration illustrates the relative stiffness of each LFRS. Models A through D are placed side-by-side on the shaking platform in pairs. The input frequency of the platform is increased gradually from 0.5 Hz. to 12 Hz. in order to excite each model in its fundamental mode. As the input frequency approaches the fundamental frequency of a particular model, its lateral deflection response reaches a maximum. By direct observation, model A has the maximum deflection response and model D the minimum deflection response of models A through D. Since each model has approximately equal height and mass participation, it can be reasonably concluded that model A has the minimum lateral stiffness and model D the maximum lateral stiffness.

The first demonstration simulates the potential hazard of pounding between adjacent structures. Combinations of two models each with a different LFRS and hence a different lateral stiffness are placed end-to-end separated by a small (approximately one inch) gap. Initially, the demonstration is performed using models A and B. Similar to the preliminary demonstration, the input frequency is gradually increased from 0.5 Hz. to 12 Hz. As the platform motion approaches the fundamental frequency of model A, the lateral deflection of model A increases until the tops of the models collide. Subsequently, the procedure is repeated for combinations of model A and other models. For each combination, the one inch gap is narrowed by 1/4 inch increments until a collision occurs. These collisions between models simulate the pounding action which may occur between structures with different lateral stiffnesses.

The second demonstration illustrates the hazard due to incompatible stiffness of building elements such as a frame with masonry infill. For this demonstration, models B, D and E are used. Model E is a hybrid of models B and D and represents a braced frame with masonry infill. In this demonstration, models are placed in a side-by-side orientation. Initially, models B and D are shaken simultaneously. The deflection response of model B is many times that of model D. This procedure is repeated using models D and E. The difference between the deflection responses of models D and E is not perceptible. Hence, models D and E have approximately identical stiffnesses. It can be concluded that the shear stiffness of the masonry infill, like a shear wall, controls the lateral stiffness while the braced frame contributes no apparent stiffness. Consequently, the masonry infill experiences forces which may be greater than its design capacity.

The third demonstration highlights the hazard of out-of-plane instability of masonry shear walls. Although such walls may provide adequate in-plane stiffness and strength, they provide significantly less out-of-plane stiffness unless braced. Model D is placed on the shaking platform and a duplicate of model D is placed in a perpendicular orientation. Initially, the models are shaken simultaneously at a low input frequency. The model aligned perpendicular to the direction of platform motion has dramatically higher deflection responses than the model aligned in the parallel direction. As the input frequency is increased, the latter model displays deflections of large magnitude and eventually becomes unstable and collapses. The model represents the behavior of a masonry shear wall unbraced in the out-of-plane direction.

Additional demonstrations can be developed to illustrate other hazards including soft stories and short columns. For this purpose, models A through E can be adapted or new models can be assembled using similar building elements. The foregoing demonstrations illustrate hazards relating singularly to superstructure behavior, in particular, the lateral force resisting system. However, to demonstrate the actual response of the structure, many other factors may play a role i.e. soil condition, damping sources and ductility. Although demonstrations using simple models can not be used to replicate actual behavior, these models can simulate the large deflections due to nonlinear behavior which may occur during severe ground shaking.

Though these models have limitations, they yield successful demonstrations. The dynamic motion of the models provides the visual component of the demonstrations while the synthesizer supplies the auditory component. The combination of these components enhances the instructional value of the demonstrations.

Demonstrations in the Virtual Environment

The advance of computer technology makes it possible to demonstrate structural hazards in a novel format. An interactive demonstration system is proposed using structural models in a computer-generated virtual environment. The system would have the capability to perform multi-sensory presentations of structural responses dependent on the needs of the intended audience. To meet this requirement, the components of the system would include the presentation software, a view screen and an interface mechanism with the audience. To permit ease of use in varied settings, the application program could be run on any high-performance personal computer, or ideally, on a notebook computer with a fast video array. The view screen may be a wide-screen monitor or an overhead projection. By incorporating multi-sensory interaction, the reality of the demonstration could be enhanced. For increased interaction, the view screen may be head-mounted to immerse the audience into the virtual environment. Optionally, simulated sound effects of an earthquake could be played simultaneously and structural responses could be input into the seats of the audience.

Several implementation strategies for model representation and display of dynamic responses are discussed in [12,13,14,15]. Although each strategy has inherent advantages and disadvantages, the strategy outlined in this paper consists of a two-step procedure using pre-computation of dynamic structural responses and real-time presentation of these responses. This implementation strategy has the advantage that time-consuming nonlinear dynamic analysis does not affect the graphical display of deflection responses. The procedure is outlined below.

In preparation for a demonstration, an appropriate finite element model is developed for each structure required in the demonstration. A dynamic time-history analysis is performed for each model to determine nodal time-history responses. Since these responses are precomputed in advance of the demonstrations, the structural analysis can be performed on any computer platform. To achieve real-time presentation of responses, the complexity of the model representation is reduced. For this purpose, simplified models are created by substructuring the original models. These simplified models incorporate the minimum number of elements required to adequately represent a 3-D structure. During a given demonstration, the presentation software displays nodal time-history responses at selected time intervals to achieve real-time or slow motion responses. Advanced graphic rendering of the elements should be avoided. In addition, sound or vibration effects may be incorporated to compliment the graphical display of model responses.

FUTURE WORK

The demonstration system using physical models will be field-tested for effectiveness with varied audiences. The proposed demonstration system incorporating computer models in a virtual environment is presently under development.

CONCLUSIONS

Demonstration systems using simple physical or computer models can simulate earthquake hazards. The hazards discussed in this paper relate to the interaction of structures with varied lateral stiffnesses. The small-scale physical models used in the outlined demonstrations capture the predominant deflection response behaviors of their respective LFRS's. These physical models are assembled using pre-fabricated elements which are commercially-available. Therefore, significantly less time is required to construct models and more time is available for engineer-educators to conduct hazard demonstrations. In this paper, demonstrations are used to illustrate three specific hazards including pounding between buildings, incompatible stiffness of elements and out-of-plane instability of masonry. However, due to inherent limitations, simple physical models can not be used to demonstrate all potential hazards for structures. Demonstrations using computer models represent a powerful alternative. Although computer models require some time to develop and analyze, dynamic analyses using computer models are able to incorporate most conditions relevant to structural behavior. Hence, computer models have the potential to yield more realistic structural responses.

The use of 3-D dynamic demonstrations may be more instructive than conventional educational approaches. The demonstration approach presents earthquake hazards in a straightforward and understandable manner which does not require detailed technical explanations. Hence, demonstrations represent a suitable technique which facilitates the transfer of hazard knowledge to audiences outside the field of earthquake design and engineering. Consequently, demonstrations can heighten the general hazard awareness of their intended audiences i.e. corporate professionals, building contractors and the general public. While this educational technique is not a panacea, it should be included in a collection of practical instructive techniques which can successfully demonstrate earthquake hazards.

REFERENCES

1. W. Howe. "Seismic Building Code Efforts in the Central United States." *Annals of the New York Academy of Sciences.* 558 (June 16, 1989): 421-434.

2. "Big Apple Seismic Code Closer to Approval." *ENR.* (April 8,1991): 27-29.

3. H. J. Lagorio, R. A. Olson and S. Scott. *Knowledge Transfer in Earthquake Hazard Education: A Challenge for Practitioners and Researchers.* Report No. CEDR-01-91, University of California, Berkeley, 1991.

4. "Subject to Change..." San Francisco, Calif.: Pacific Bell, 1988.

5. "Earthquake Risk to the Central U.S." Washington, DC: Federal Emergency Management Agency, 1988.

6. "When the Earth Quakes." Washington, DC: National Geographic, 1990.

7. D. A. Wiltshire, M. E. Powell andd P. R. Stevens. "Geomedia: A Multimedia Education System for Elementary School Children." *Scientific Visualization Workshop.* Reston, Virginia: Joint United Stated Geological Survey/Jet Propulsion Laboratory, 1992.

8. H. McLellan. "Virtual Environments and Situated Learning." *Multimedia Review.* (Fall, 1991): 30-36.

9. R. V. Whitman. "Engineering Issues of Earthquake Hazard Mitigation in Eastern North America." *Annals of the New York Academy of Sciences.* 558 (June 16, 1989): 11-20.

10. C. Arnold. "Architectural Considerations." *The Seismic Design Handbook.* Edited by F. Naeim. New York: Van Nostrand, 1989.

11. V. Caccese and H. G. Harris. "Earthquake Simulation Testing of Small-Scale Reinforced Concrete Structures." *ACI Structural Journal.* 87 (Jan.-Feb., 1990): 72-79.

12. M. A. Tarlton and P. N. Tarlton. "A Framework for Dynamic Visual Applications." Proceedings of SIGGRAPH '92, *Computer Graphics*. 26 (July 1992): 161-164.

13. A. Pentland and J. Williams. "Good Vibrations: Modal Dynamics for Graphics and Animation." Proceedings of SIGGRAPH '89, *Computer Graphics*. 23 (July 1989): 215-222.

14. S. J. Teller and C. H. Sequin. "Visibility Pre-Processing For Interactive Walkthroughs." Proceedings of SIGGRAPH '91, *Computer Graphics*. 25 (July 1991): 61-69.

15. T. A. Funkhouser, C. H. Sequin and S. J. Teller. "Management of Large Amounts of Data in Interactive Building Walkthroughs." Proceedings of SIGGRAPH '92, *Computer Graphics*. 26 (July 1992): 11-20.

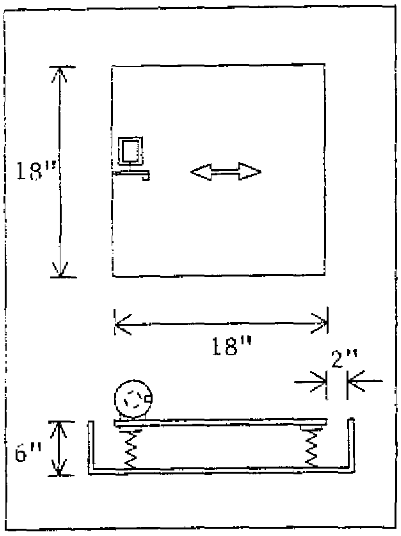

FIGURE 1. System configuration.

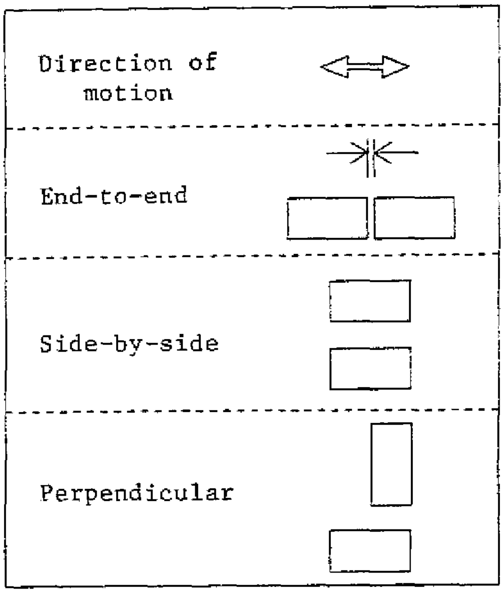

FIGURE 3. Model orientations.

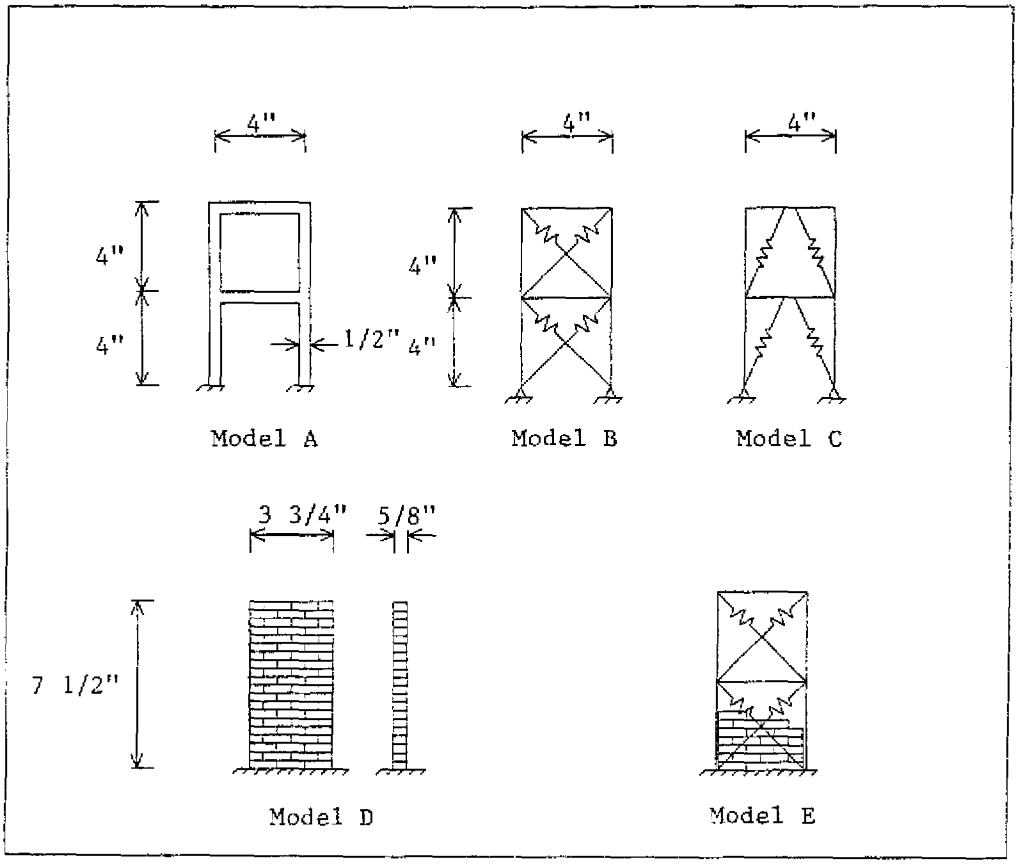

FIGURE 2. Model elevations.