J. SE Asian Appl. Geol., Sep–Dec 2010, Vol. 2(3), pp. 225–231

EARTHQUAKE DISASTER MITIGATION USING INNOVATIVE RETROFITTING METHOD

Eric Augustus J. Tingatinga*[1] and Hideji Kawakami[2]

[1]*Institute of Civil Engineering, University of the Philippines, Diliman Quezon City, Philippines*
[2]*Geosphere Research Institute of Saitama University (GRIS), Saitama Japan*

Abstract

The Philippines, because of its geographic location, has been battling the onslaught of natural hazards. About 20 tropical cyclones visit the country every year, active volcanoes erupt within few decades, and earthquakes frequent the country causing damages to structures. Field studies have reported that the casualties and damages due to strong earthquakes have been attributed mainly to collapse of civil engineering structures. Therefore, in order to guarantee the safety of the general public in the event of future earthquakes, it is necessary to study the mechanisms of collapse of these built structures and to provide ways to identify their weak points for the benefit of retrofitting. To address the above issues, a new methodology was developed for the seismic performance assessment of structures. This methodology identifies local failures such as column buckling and connection fracture, which may induce the global system to collapse. In this study, a three-dimensional rigid body-spring method, which can describe the inelastic behavior of a structure and simulate the progressive collapse process, was employed. The sequence of the analysis and results in the form of computer animations offer a real-time assessment of the structural integrity of buildings during earthquakes.

Keywords: *Collapse, damage, buildings, rigid body-spring method, simulation*

1 Introduction

The Philippines has been battling the onslaught of natural hazards. This is not surprising considering its geographic location. Yearly, about 20 tropical cyclones visit the country and about five of them may cause significant damages. The Philippines also has 220 volcanoes; 22 of which are considered active that had erupted in the last 10,000 years.

The country also has a complex tectonic setting (islands are sandwiched between two opposite subduction zones) and Luzon Island shows high seismic activity. The 1990 Luzon earthquake is considered to be the strongest and most fatal of all earthquakes generated by this fault zone. And like most deadly earthquakes, the death toll was reported to be mostly caused by collapse of buildings.

The collapse of engineering structures is a clear manifestation of not only strength of an earthquake, but also the inadequacy of seismic code provisions in an area and poor construction method of buildings. While the former is beyond human control, the consequences due to the latter may be mitigated. It is essential, therefore, for engineers to analyze the mechanisms of collapse of buildings as well as toppling of office and household utilities during strong motion earthquakes.

The evolution in computer hardware has remarkable impact on engineering analysis and design. Computer experiments utilizing state-of the-art computer techniques such as multimedia, realistic computer graphics and animation reinforce, if not replace, traditional ex-

---

*Corresponding author: E.A.J. TINGATINGA, Institute of Civil Engineering, University of the Philippines, Diliman Quezon City, Philippines. E-mail: eatingatinga@gmail.com pensive experiments. Recent efforts to simulate earthquake response due to strong motion earthquakes attracted many researchers in the field of architecture, structural and earthquake engineering.

This study presents a three-dimensional simulation of structure collapse during strong motion earthquakes, such as the 1995 Great Hanshin Earthquake, using Rigid Body-Spring Method (RBSM). Various modes of collapse of a wooden structure modeled as an assembly of rigid bodies connected by rigid links at their ends will be presented. In modeling structural components, a link configuration is suggested utilizing a Kelvin link to take into account structural damping and elasto-plastic behavior. Being vital in computer graphics and animation, collision detection, collision response, contact handling, and the accuracy of the integration method of the animation system have been comprehensively investigated.

Summary of previous works

While Isobe and Toi (1998) used Adaptively Shifted Integration (ASI) technique to perform seismic damage analysis, most researchers (Meguro and Katayama (1997), Ren et.al. (1999), Tagel-Din and Meguro (2000), Kuwata and Takada (2004), Kiyono and Furukawa (2006)) have developed methods based on the distinct element method originally proposed by Cundall (1971). With regards to simulating dynamic response and collapse of wooden houses during strong earthquakes, previous works were limited to one-story building models, or frame models or buildings subjected to two-dimensional seismic wave. Furthermore, although some researchers validated their work using real experiments in full-scale, e.g. Sakamoto, et.al. (2006), details of the numerical method used and the modeling of structural components are not extensive.

This study proposes three-dimensional rigid body-spring method to be use in collapse simulations. Rigid body spring method can simulate, using detailed modeling, the onset of collapse such as joint failures, and can accurately simulate the progress of collapse by considering collision and contact forces natively. The theory has been extensively discussed by several researchers in the fields of computer graphics/animation and robotics, e.g. Baraff (1992), Witkin and Baraff (2001), and will not be discussed in detail in this thesis. In modeling beams and columns, multi-spring models similar to that introduced by Lai, et. al. (1984) and Li and Otani (1993) in simulating hysteretic behavior of RC members, are utilized. Each spring exhibits nonlinear restoring force-deformation relation and may demonstrate hysteresis based on the models discussed by experimental researchers (see Otani (1981))

2 Rigid body simulation

In rigid body-spring method, the basic approach is to divide the given structure into appropriate number of rigid elements connected by spring systems between elements. The displacements are completely described by the position and rotations of the rigid bodies while the deformation energy of the structural element is stored only in the spring system.

Motion equations

To animate various systems using rigid bodies, appropriate forces must be taken into account. Forces that arise due to relative positioning of objects (e.g. contact, collision), object's velocity, connections (e.g., spring, damper), and user-specified vector fields (e.g. gravity, other external forces) must be exerted on bodies properly. These forces induce linear and angular accelerations depending on the mass and mass distribution of the body, respectively.

The two fundamental equations used to analyze motion of rigid bodies in space are

$$\sum F = m\ddot{r} \tag{1}$$

$$\sum M_G = \dot{H}_G \tag{2}$$

where $\ddot{r}$ is the acceleration of the center of mass and $\dot{H}_G$ is the rate of change of the angular momentum about the mass center of the rigid body.

Simulation of earthquake motions

It is a well-known fact in structural dynamics that the displacement or deformation $u(t)$ of the structure due to ground acceleration $\ddot{u}_g(t)$ will be identical to the displacement or deformation of the structure if its base were fixed and if it were subjected to an external force equal to $-m\ddot{u}_g(t)$. Therefore, to simulate earthquake motion in rigid body systems, an effective earthquake force (inertial force) which is equal to the rigid body mass times the ground acceleration and acting opposite to the acceleration will be exerted.

Moreover, to obtain more realistic animations, *absolute motion* of objects must be simulated by viewing it from a fixed frame or location not attached to the ground. For this purpose, the animation camera is moved in a direction opposite the ground displacement.

Throughout the scope of this paper, the earthquake accelerogram used was that of the 1995 Kobe earthquake. The maximum accelerations in EW-, NS-, and UD-directions are 0.6g at 5.46 s, 0.83g at 5.52 s, and 0.3g at 4.72 s, respectively. Figure 1b shows the corresponding displacement-time history used in moving the animation camera.

3 Nonlinear response analysis

System of Kelvin links

A new link consisting of a spring and a damper, parallel to one another is introduced. Since it is analogous to a Voigt/Kelvin element in modeling viscoeleastic materials in mechanics of materials, it is herein named as a Kelvin link. Forces exerted to points on connected bodies is the vector sum of spring and damper components.

The stress-strain behavior of materials, as modeled by springs, is idealized by the straight lines in Figure 2. In the tensile region, the restoring force is proportional to the strain up to ε_{1T} with maximum yield restoring force F_{YT}. The second straight line represents in an idealized fashion; the strain-hardening range comes until breaking point C when the restoring force reach its ultimate value F_{UT}.

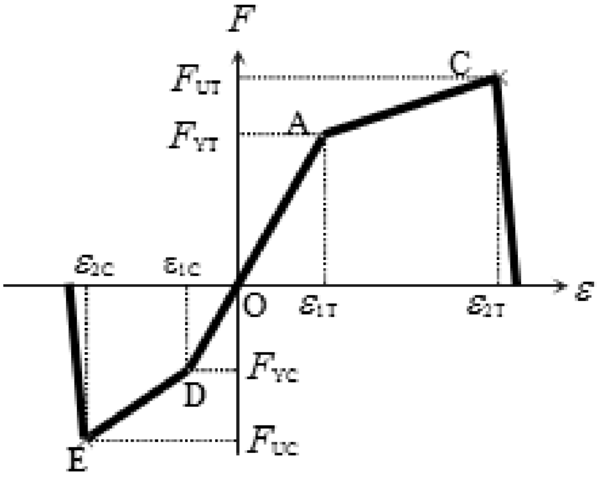


Figure 2: Force exert

A new link configuration is introduced to model plastic hinges at the end of beams and columns. It consists of 12 Kelvin links positioned to model axial, shear, and bending deformations (see Figure 3)

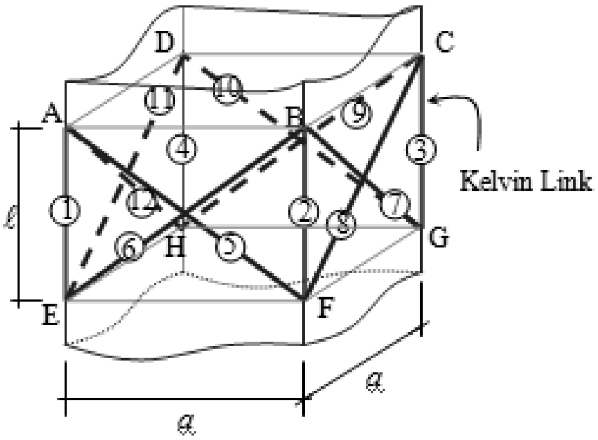
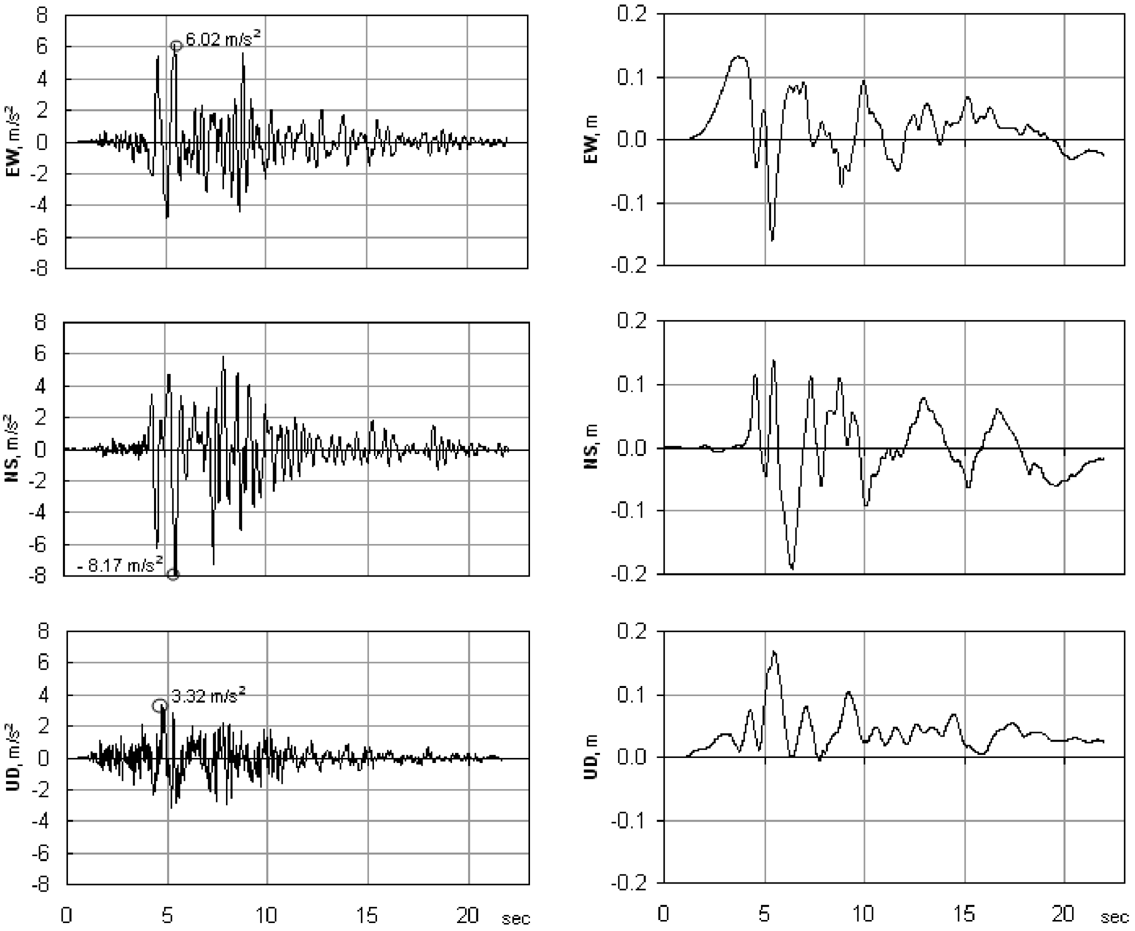


Figure 3: Plastic hinge

Typical modes of collapse of wooden houses

Consider modeling wooden houses as shown in Figure 4. The dead load of the floor slab, beams, columns, walls and roofs, and the live load are estimated. The stress-strain curves for the material of the structural members are modeled and are used.

Using the numerical method presented in the previous section, earthquake responses of typical wooden houses in Japan were computed.



(a) (b)

Figure 1: Time history of (a) ground acceleration and (b) ground displacement of the 1995 Kobe earthquake used in analyses

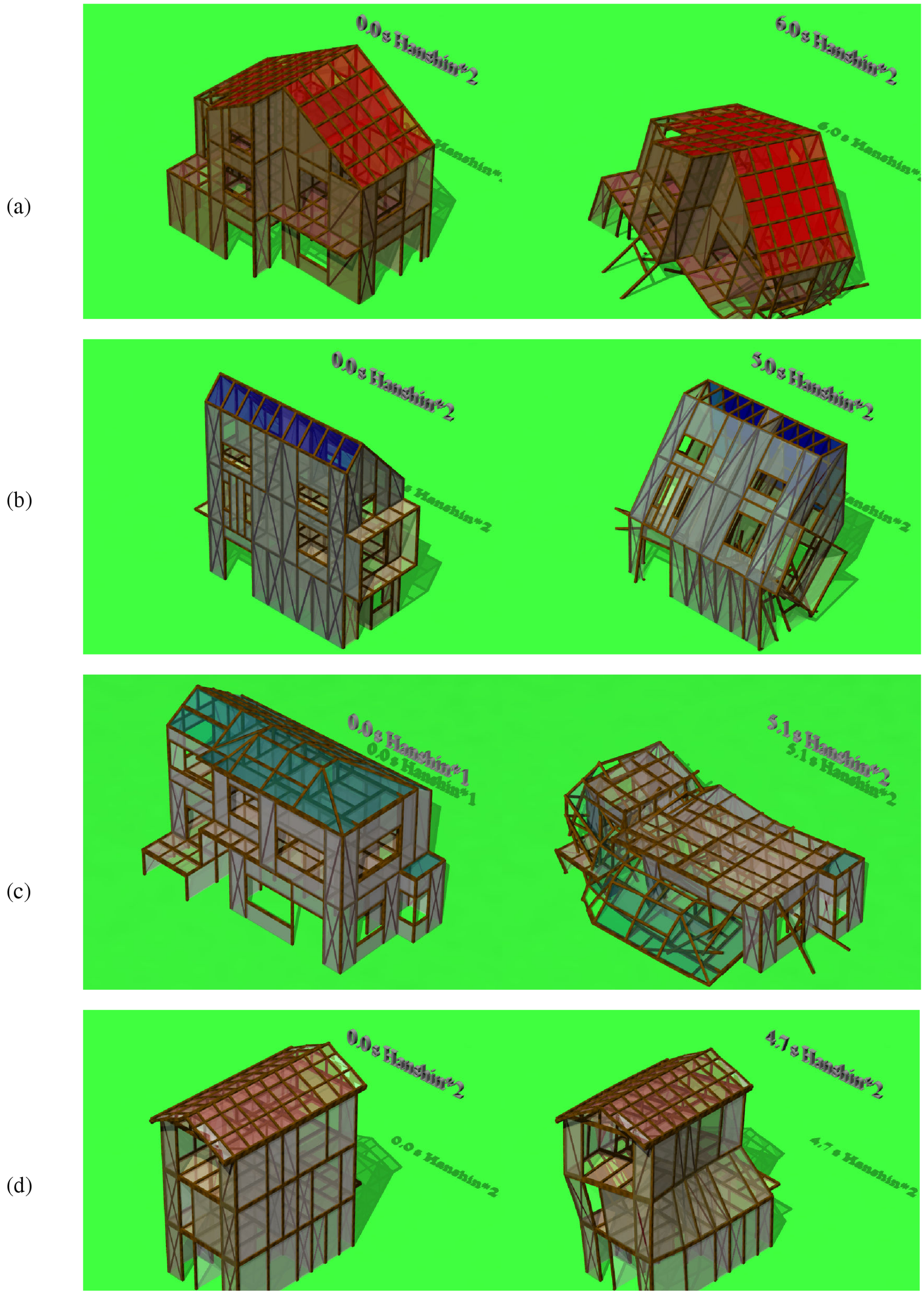


Figure 4: Collapse mechanisms of typical wooden house

In modeling, the dead load of the floor slab, beams, columns, walls and roofs, and the live loads were estimated. The stress-strain curves for the material of the structural members were taken into account. The model structures were then subjected to doubly-amplified waves of the 1995 Kobe earthquake in Figure 1.

Figures 4a-d show various collapse mechanisms of wooden houses including (a) collapse due to the soft first story, (b) tumbling type collapse, (c) failure at the second floor due to the amplification of the vibration at the upper floor, and (d) collapse of intermediate floor. Even though the soft first story type of collapse is often stressed, the failure mechanism depends on the design and physical layout of the structure, i.e., strength and distributions of columns, beams and walls.

Retrofitting Example

When wooden houses need structural reinforcement, structural engineers must confer with the building owner before carrying out appropriate retrofit methods. A retrofit plan may not be implemented if the structural engineer can not have the building owner understand the performance assessment of the building. The method presented in the previous sections was developed for the purpose of seismic performance assessment and retrofit strategy for woodframed buildings.

As shown in the examples, the sequence of the analysis and results in the form of computer animations allow engineers to identify local failures such as column buckling and connection fracture, which may induce the global system to collapse. This method, therefore, is useful in reinforcing the system by adding stiffness or strength to the weak members.

In order to avoid the collapse, several retrofit plans were developed such as shown in Figures 5(a) and (b), where the black walls indicate those reinforced by diagonal braces and structural boards. The method proposed in this study as described was then used to simulate the earthquake response of each of the reinforced houses. Results showed that the house in Figure 5(a) withstood the same earthquake motions used in Figure 1, i.e., the doubly-amplified waves of the 1995 Kobe earthquake. The house in Figure 5(b) also resisted the strong ground motion but the reinforcement was not as efficient as that employed in Figure 5(a). Based on the obtained results, therefore, engineers can propose retrofit plans so house owners can improve the performance of their houses against earthquakes.

4 Summary and conclusions

This paper attempted to simulate seismic collapse of wooden houses subjected to the 1995 Kobe earthquake using the Rigid Body-Spring Method (RBSM), and the following conclusions were drawn:

1. The simplified model of wooden houses is capable of demonstrating, to some extent, various collapse behaviour during strong motion earthquakes. More accurately, the link system used to characterize plastic hinges can simulate local failure that causes the entire house to collapse during strong motion earthquakes.
2. The method provides a way to identify the weak point of a structure, thus allowing engineers to perform retrofitting analysis easily so as to suggest ways to improve the seismic performance of built wooden houses.

References

Cundall, P.A. (1971). A computer model for simulating progressive large scale movements in blocky rock systems, ISRM Symposium, Nancy, France, Proc. 2, pp. 129-136.

Isobe, D. and Toi, Y. (1998) ASI finite element analysis of dynamic collapse behaviors of framed structures considering member fracture. Proceedings of the 4th World Congress on Computational Mechanics, Buenos Aires, Argentina.

Kiyono, J. and Furukawa, A (2006). Bracing effect mechanism in the collapse of timber-frame houses due to earthquake and snow weight. Journal of Natural Disaster Science: Vol. 28, No. 1, pp. 1-13.

Kuwata, Y. and Takada, S. (2004) Collapse of wooden houses considering instantaneous instrumental seismic intensity. Asian Journal of Civil Engineering (Building and Housing); 5(1-2).

(a)

(b)

Figure 5: Two examples of reinforcement plans of the wooden house. The walls shown in black are reinforced by diagonal braces and structural boards

Lai, S.-S. (1984). Model for inelastic biaxial bending of concrete frames. ASCE Journal of Structural Engineering; Vol. 110, No. 11, November 1984, pp. 2563-2584.

Li, K.-N. and S. Otani, S. (1993). Multi-spring Model for 3-Dimensional Analysis of RC Members, Journal of Structural Engineering and Mechanics, Vol. 1, No. 1, pp. 17-30.

Meguro, K. and Katayama, T. (1997) Simulation of collapse process of elevated expressway bridges due to the Kobe earthquake. Proc. of the Workshop on Earthquake Engineering Frontiers in Transportation Facilities, Post-Earthquake Reconstruction Strategie, NCEER-INCEDE Center-to-Center Project, Technical Report NCEER-97-0005/INCEDE Report No.1997-01, pp. 155-162

Otani, S. (1981). Hysteresis Model of Reinforced Concrete for Earthquake Response Analysis, Journal of Faculty of Engineering, University of Tokyo, Series B, Vol. XXXVI-II, No. 2, pp. 407-441.

Ren, W.-X., Tan, X. and Zheng, Z. (1999) Nonlinear analysis of plane frames using rigid body-spring element method. Computers & Structures, 71(1): 105-119.

Sakamoto, I. et al. (2006) Wood Building Collapse Test Using E-Defense, Technical Memorandum of Public Works Research Institute, No. 4022, pp. 87 (in Japanese) , 2006.

Tagel-Din, H. and Meguro, K. (2000) Analysis of small scale RC building subjected to shaking table tests using applied element method. Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand.

Witkin, A. and Baraff, D. (2001). Physically Based Modeling - ONLINE SIGGRAPH 2001 COURSE NOTES, Pixar Animation Studios, http://www.pixar.com/companyinfo/research/pbm2001/.