SEISMIC COLLAPSE ANALYSIS OF WOODEN HOUSES IN JAPAN USING NONLINEAR RIGID BODY-SPRING METHOD

H. Kawakami[1] and E.A. Tingatinga[2]

[1] *Professor, Geosphere Research Institute, Saitama University, Saitama, Japan*
[2] *PhD Student, Graduate School of Science and Engineering, Saitama University, Saitama, Japan*
Email: kaw@kiban.civil.saitama-u.ac.jp, eatingatinga@gmail.com

ABSTRACT :

In Japan, the majority of modern residential buildings are wood-framed construction and the past few decades revealed the vulnerability of these structures to strong earthquakes. The Kobe earthquake in 1995 caused tremendous loss of lives resulting from the collapse and damage of wooden houses. This disaster motivated many researchers to study the mechanisms of collapse of engineering structures in order to prevent further loss of lives in the future. In this paper, an innovative methodology in simulating the dynamic response of wood-framed residential buildings, for purposes of seismic performance assessment and retrofitting, is presented. The proposed method, which can simulate inelastic behavior of structures, is capable of showing realistic progressive collapse mechanisms and accurate seismic response of structures. The sequence of analyses and results in the form of computer animations provide real-time assessment of structural integrity and a way to identify the weak points of a structure. Applications to real wood-framed residential buildings were used to show the effectiveness of the methodology in seismic performance assessment and in retrofitting.

KEYWORDS: wooden houses, collapse, retrofitting, rigid body-spring method, simulation

1. INTRODUCTION

The evolution in computer hardware has significant impact on computing science and engineering design. Desktop and portable computers nowadays are operating at tremendous speed, have huge memory resources and even multiple processors, thereby permitting very fast computations never conceived before. Because of these advancements, several researches have been conducted to simulate various natural phenomena and to analyze problems that were previously infeasible.

Efforts to simulate response of built structures to strong motion earthquakes attracted many researchers in the field of architecture and civil engineering. One of the most familiar accelerogram used is that of the Kobe earthquake in Japan which occurred in January 17, 1995 and caused enormous damage and destruction of structures and deaths in Kobe and in nearby areas. The death toll was reported to be mostly caused by collapse of buildings and breakdown of other civil engineering facilities. Investigation further revealed that most deaths were due to collapse of conventional wooden houses.

Wooden houses, as well as traditional wooden architectures, in Japan are characterized by tiled and heavy roof made of clay. These structures are very vulnerable to strong earthquakes (as depicted in Photo 1) and the loss that may result as a consequence of its collapse have proved to be irreplaceable. Because of these, structural and earthquake engineers study the mechanisms of collapse of each wooden house and building in order to guarantee the safety of the general public in the occurrence of future earthquakes.

Although several researchers have conducted experiments to study collapse mechanisms in full-scale such as those conducted at E-Defense located in Miki City, Japan, numerical simulation attracted other researchers to perform nonlinear analysis using computers. Computer simulations are justified by the following facts:
1. Actual experimental set-ups are very expensive, takes more time, and are subject to physical limitations such as limitations on the maximum velocity or displacement of shaking tables, etc.

Photo 1 Damage to wooden houses due to the 2007 Niigata-ken Chuetsu-oki earthquake in Japan

2. Computer hardware, nowadays, offers ability to perform fast computations to allow analysis of an entire structure using desktop computers. Computer simulations also allow researchers to validate the effectiveness of different retrofitting techniques.

Experimentation plays a very important role in the assessment of accuracies of collapse predictions and simulations, but the above reasons have paved the way to the development of different numerical techniques. The popular Finite Element Method (FEM) allows modeling of structures at the material level, but its computational complexity has restricted its application to analysis of basic structural elements such as beams, columns, and joints. Finite element analysis of an entire structure was regarded to be too complex and that dynamic analysis exhibiting strong nonlinearity and discontinuity requires a lot of computer power. Because of this, other approaches have been developed to allow analysis of the seismic response of engineering structures.

This study presents a three-dimensional simulation of structure collapse during strong motion earthquakes, such as the 1995 Kobe earthquake, using Rigid Body-Spring Method (RBSM). Various modes of collapse of a wooden structure modeled as an assembly of rigid bodies connected by inelastic links at their ends, will be presented. In modeling structural components, a link configuration is suggested to take into account structural damping and inelastic behavior.

The main objectives of this study are to understand the process in which wooden houses collapse during earthquakes and to identify and reinforce the weak point of the structure. Specifically, it aims to
1. simulate collapse mechanisms by modeling structural elements using RBSM implementing a configuration of inelastic links;
2. investigate how the collapse progresses from the local failures of the framing members; and
3. propose, with the use of an example, ways to reinforce a house to withstand strong ground shaking.

2. NONLINEAR ANALYSIS USING ASSEMBLY OF RIGID BODIES

Originally proposed by Kawai (1977), the basic approach of RBSM is to divide the given structure into appropriate number of rigid elements connected by spring systems. The displacements are completely described by the positions and rotations of the rigid bodies while the deformation energy of the structure is stored in the spring system.

In this paper, nonlinear analysis of structures will be carried out by introducing nonlinear springs to take into account large displacements and failure of structures during strong motion earthquakes.

Motion equations (Baraff 1992; Hamilton 1847)
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., springs, dampers), and user-specified vector fields (e.g., gravity, other external forces) must be exerted on bodies properly. These forces, as shown in Fig. 1, 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

$$\sum \boldsymbol{F} = m\ddot{\boldsymbol{r}} \tag{2.1}$$

$$\sum \boldsymbol{M}_G = \dot{\boldsymbol{H}}_G \tag{2.2}$$

where $\ddot{\boldsymbol{r}}$ is the acceleration of the center of mass and $\dot{\boldsymbol{H}}_G$ is the rate of change of the angular momentum about the mass center of the rigid body. If x, y and z axes coincide with the principal axes of inertia of the rigid body as shown in Fig. 1, Eqn. 2.2 reduces to the well known Euler's equations of motion and is expressed

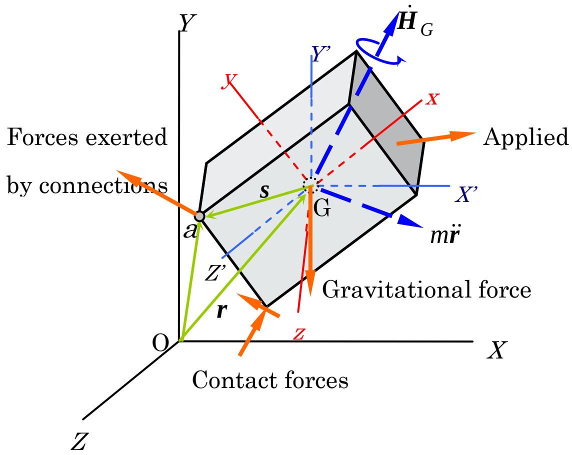

Figure 1 Applied and effective forces on a rigid body and coordinate systems used in computer animation.

in terms of the inertia tensor $\sum \boldsymbol{M}_G = \boldsymbol{I}\dot{\boldsymbol{\omega}}$.

At any instant, the state of a rigid body is stored in a vector $\boldsymbol{x}(t)$ consisting of its position, orientation (expressed in this text using Hamilton's (1947) *quaternion* $\boldsymbol{q}$), and its linear and angular velocities. Mathematically collected as,

$$\boldsymbol{x}(t) = \begin{Bmatrix} \boldsymbol{r}(t) \\ \boldsymbol{q}(t) \\ \boldsymbol{v}(t) \\ \boldsymbol{\omega}(t) \end{Bmatrix}_{13\times 1} \tag{2.3}$$

By assuming that $\boldsymbol{v} = \dot{\boldsymbol{r}}$ and using the properties of a quaternion, we can rewrite Eqns. 2.1 and 2.2 as the time derivative of the state vector

$$\dot{\boldsymbol{x}}(t) = \begin{Bmatrix} \boldsymbol{v}(t) \\ \frac{1}{2}\boldsymbol{\omega}(t) * \boldsymbol{q}(t) \\ \sum \boldsymbol{F}(t)/m \\ \boldsymbol{I}^{-1}(t) \cdot \sum \boldsymbol{M}(t) \end{Bmatrix} \tag{2.4}$$

where $\boldsymbol{\omega}(t) * \boldsymbol{q}(t)$ denotes a shorthand of the multiplication of two quaternions $[0, \boldsymbol{\omega}(t)]$ and $\boldsymbol{q}(t)$.

This system of first-order differential equations are sufficient to perform physically based animation of rigid bodies. Knowing the current state of the rigid bodies and the derivative information at any time, a differential equation solver can now be used to compute the state vector at a subsequent time $\boldsymbol{x}(t+h)$. Euler method, as given in Eqn. 2.5, for example can be used but since it is unstable and inaccurate, more sophisticated methods such as Runge-Kutta method are appropriate. Although they are more computationally expensive than Euler method, large step sizes can be used resulting in an overall computational savings.

$$\boldsymbol{x}(t+h) = \boldsymbol{x}(t) + h \cdot \dot{\boldsymbol{x}}(t) \tag{2.5}$$

Finally, it is important to note that the sum of forces and sum of moments about rigid body's mass center in Eqn. 2.4 include contact and collision forces (or impulses) when it moves relative to another rigid body. This, of course, entails the use of efficient algorithms for collision detection and collision response but will not be further discussed in this paper.

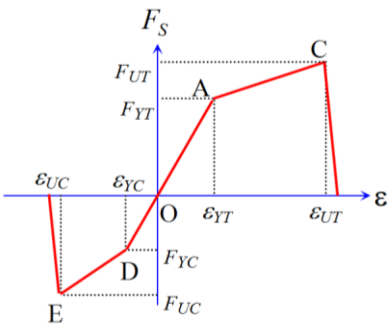

Figure 2 Force exerted by a link on rigid bodies

3. EARTHQUAKE GROUND MOTIONS

Throughout the scope of this paper, the earthquake accelerogram used was that observed at Kobe Marine Meteorological Observatory during of the 1995 Kobe earthquake. The maximum accelerations in EW-, NS-, and UD-directions are 6.0 m/s^2 at 5.5 s, 8.2 m/s^2 at 5.5 s, and 3.3 m/s^2 at 4.7 s, respectively.

4. SYSTEM OF NON-LINEAR SPRINGS AND DASHPOTS

In this study, several hysteresis models were implemented to simulate behaviour of different structural materials. Although, most of the models were originally developed by experimental researchers for dominantly flexural behaviour of reinforced concrete, some may be applicable to wooden structures, and whenever appropriate, we can always assume a multi-linear restoring force such as that shown in Fig. 2.

The stress-strain behavior of materials, as modeled by springs, is idealized by the straight lines in Fig. 2. In this model the restoring force in tension is proportional to the strain up to ε_{YT} with maximum yield restoring force F_{YT}. The second straight line represents the strain-hardening characteristic until point C, when the restoring force reaches its ultimate value F_{UT}. For different set of parameters (ε_{YC}, F_{YC}, ε_{UC}, and F_{UC}), the behavior in compression can be modeled. If the strain in the link exceeds its maximum value ε_{UT} or ε_{UC}, no subsequent forces are exerted to the connected bodies. The link is marked DELETED to aid analysis of link failure.

To simulate structural damping, we use nonlinear viscous damper installed parallel to each spring.

5. APPLICATION TO CONVENTIONAL WOODEN HOUSES

Using the numerical method presented in the previous sections, earthquake responses of typical wooden houses in Japan were computed. 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 modeled. The model structures were then subjected to doubly-amplified waves of the 1995 Kobe earthquake, and various collapse mechanisms of wooden houses were observed 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. For example, Fig. 3 shows the response sequences of two two-storey wooden houses with different strengths or reinforcements. During the strong motion earthquake, the house (a) with the red members indicating diagonal braces deformed beyond the limit of linearly elastic behavior, and the southern portion of the first floor began to fail at around 5 s, and collapsed at about 6 s.

However, the house (b) in Fig. 3(b) withstood the same earthquake motions used in Fig. 3(a), i.e., the approximately doubly-amplified waves of the 1995 Kobe earthquake.

Based on the obtained results, the method has been shown to be an innovative strategy for retrofitting. Engineers can easily propose retrofit plans so house owners can improve the performance of their houses against earthquakes.

6. RELIABILITY OF SIMULATED RESPONSE

Most wooden houses in Japan are generally composed of frame units made of columns and beams, and walls. Therefore, in order to establish the reliability and correctness of collapse simulation of an entire house, it is obligatory to show the agreement of simulated and experimental results for such structural units. Wooden frames with different types of reinforcements, i.e., (1) no end connection plate; (2) end connection plates; (3) plaster board; (4) siding board; (5) two single braces, plaster board and siding board; and (6) two double braces, plaster board and siding board, are considered. A monotonically increasing force was then applied horizontally to the upper beam of each frame, and the response was computed using the same program that was used in Fig. 3.

Based on the obtained response of the upper beam, the relationship between the displacement and force was plotted for each frame unit (1) through (6), and was compared with the experimental relationships obtained by Miyoshi et al. (2001). The numerical and the experimental curves agree well including the rigidity in small strain, the maximum strength, and the weakening process, and this shows the reliability of the simulation in this paper.

7. CONCLUSIONS

This research attempted to simulate seismic collapse of wooden houses subjected to the 1995 Kobe earthquake using the Rigid Body-Spring Method (RBSM) for the purpose of retrofitting. The following conclusions can be drawn:

1. The proposed method is capable of demonstrating to some extent various collapse behavior of wooden houses during strong motion earthquakes. More accurately, the link system used to characterize plastic hinges of the simplified structural components 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 and to suggest ways to improve the seismic performance of built wooden houses.

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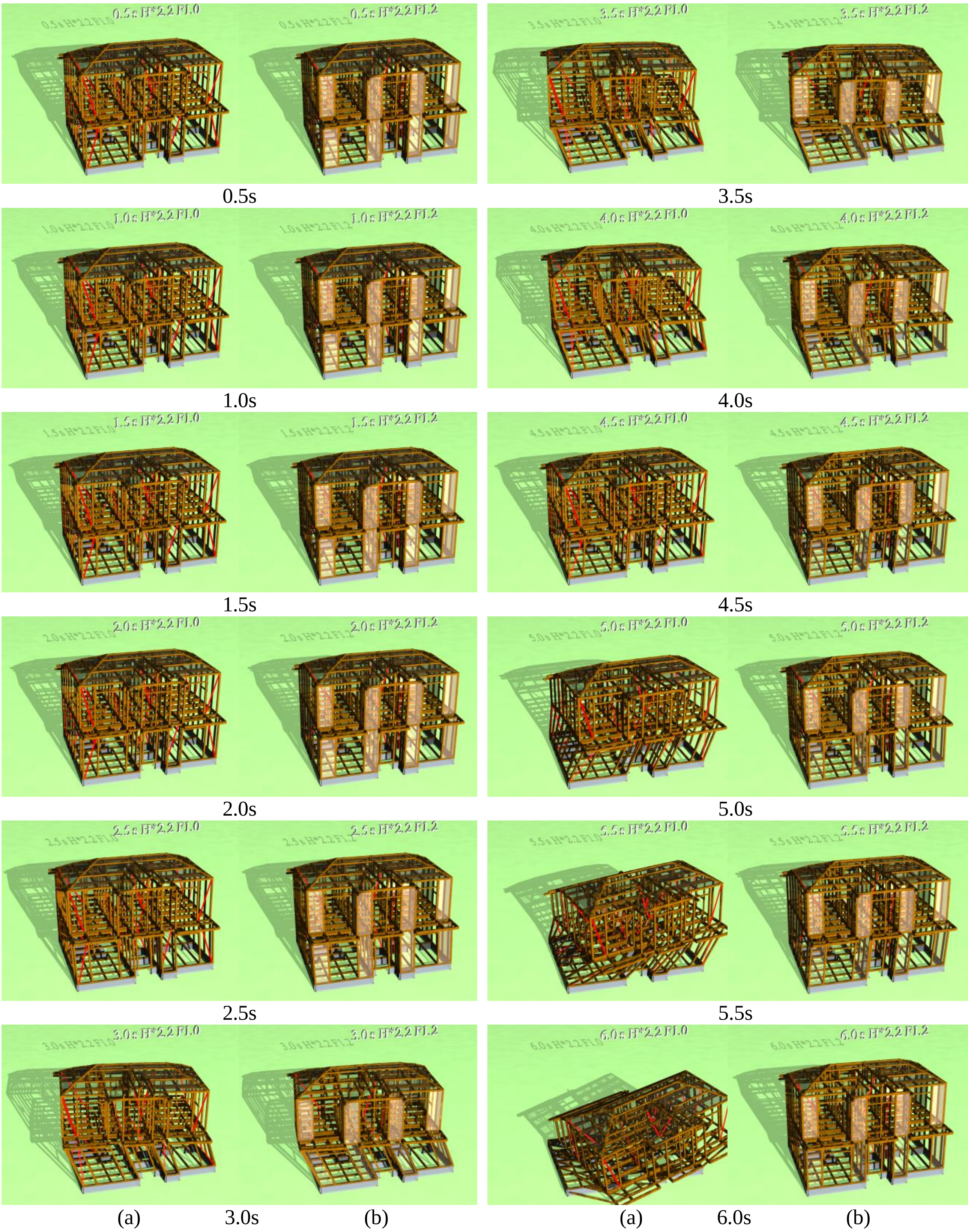

Figure 3 Response sequence of two two-storey wooden houses with different strengths or reinforcements

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