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ORIGINAL ARTICLE

Takafumi Nakagawa · Masamitsu Ohta

Collapsing process simulations of timber structures under dynamic loading I: simulations of two-story frame models

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Abstract In this study we tried to develop an analysis program that can simulate the collapsing process of timber-frame structures under dynamic loading by adopting the extended distinct element method (EDEM). Using the EDEM, it is possible to trace the movement of any parts that were separated from unity after the failure of connecting elements, a property that fits our purpose well. As a preliminary study, simple two-story frame structures were modeled and examined by our program. Each model is an assembly of frame members composed of the EDEM elements. The spring elements of the joints have less rigidity than those of the frame members. Several models were analyzed under dynamic loading. The models varied in the configuration of bracing shear walls. Experiments with a one-ninth model were carried out under similar conditions, and the results were compared with the results from numerical simulations. Simulated results showed various collapsing processes corresponding to the arrangement of the bracing shear wall, and the simulated aspects gave good agreement with the results of the experiments under similar conditions.

Key words Bracing shear wall · Distinct element method · Computer simulation · Timber-frame structure

Introduction

For aseismatic design of wooden structures, it is essential to obtain sufficient knowledge of their vibrational properties. Various analyses have been undertaken for this purpose. The characteristic frequency analysis is a well-known, simple method for investigating the vibrational response of wooden structures.[1] This method enables us to investigate the vibrational mode and damping properties of structures, but it has some difficulty with the analysis of nonlinear large deformation behavior. The time history response analysis by the shear mass system model,[2] the so-called stick-of-dumplings method, can unveil maximum deformation and nonlinear deformation for seismic loading. This method, however, is not sufficiently effective to determine the local deformation and three-dimensional torsion of a whole structure.

These characteristic factors can be clarified in detail using the three-dimensional elastoplastic analysis by the finite element method (FEM)[3,4] or by the pseudo-three-dimensional analysis.[5,6] Nevertheless, it is difficult for the FEM to simulate the failure of developing processes under dynamic loading. Furthermore, detailed damage information involving bending deformation and fracture aspects (e.g., buckling of a brace, rupture during the bending of columns, rupture of metal connections) of frame structures have hardly been determined by the above-mentioned methods.

To obtain full knowledge of the fracturing behavior of timber structures under seismic loading, it is indispensable to simulate the collapsing process and trace the movement and deformation of each structural member. Collapsing simulations are extremely useful for antiseismic planning of wooden houses because they enable us to make a seismic estimation of each wooden structure with various structural members and reinforcement of virtual spaces. It would also provide extensive economizing by not having to make real size shaking table experiments.

We tried to simulate the collapsing process of timber-frame structures numerically using a newly developed computer program. We employed the extended distinct element method (EDEM) as the base program and modified it to fit the analysis of timber structures.

T. Nakagawa (✉) · M. Ohta
Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
Tel. +81-3-5481-5253; Fax +81-3-5684-0299
e-mail: nakagawa@a.fp.a.u-tokyo.ac.jp

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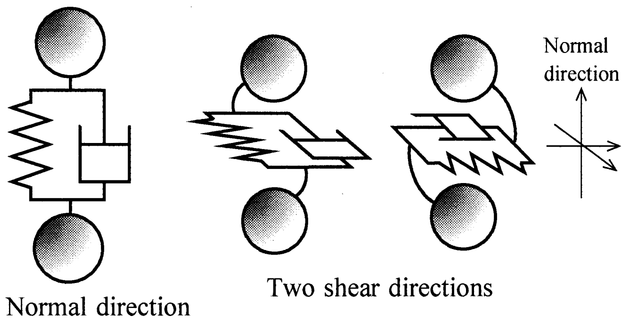

Fig. 1. Configuration of spring elements of the extended distinct element method (EDEM)

Background of EDEM

The distinct element method (DEM) was originally proposed by Cundall[7] in 1971 to simulate soils in the domain of civil engineering. With the DEM, a material is considered to be an assembly of circular particles, and there are no resistant forces against traction. To give continuity to this discrete numerical model, elastic springs and dashpots were added by some Japanese researchers, as shown in Fig. 1.[8] This method is called the "modified DEM" or "extended DEM." The model behaves as a continuous medium while the springs are intact; after the breakage of some of the springs, it enables us to trace the movement of the individual parts that were separated from each other to destroy the structure's unity. Using this method, it becomes possible to analyze the fracture-developing processes. One of the authors has applied the EDEM to the simulation of the various fracturing processes of wood and has obtained good results.[9–12]

Theories

To simulate the collapsing process of three-dimensional wooden-frame structures by EDEM, it is necessary to extend our program to a three-dimensional one. With the EDEM, material is considered to be an assembly of spherical particles called "particle elements." Particle elements are connected to each other by elastic springs and dashpots. Between two particle elements, a pairing of a spring and dashpots exists in the normal direction (along the line connecting the center of the particle elements), and two pairs exist in two shear directions, as shown in Fig. 1. These three pairs of spring and dashpots make up one spring unit, which we hereafter simply call a "spring element." These spring elements are eliminated when a fracture condition is satisfied. To save the required memory by the EDEM program, we tried to reduce the number of particle elements by simplifying the component. Each member of the wooden structure (i.e., column, sill, beam, brace, metal connector) has four particle elements in its cross section, as shown in Fig. 2a. Figure 3 shows the configuration of the spring elements connecting eight particle elements in an elementary unit, where 16 spring elements are equipped in vertical, horizontal, and diagonal directions. The frame element consists of elementary units; and by assembling the frame elements, we can obtain a frame structure model (Fig. 2b,c). At the connecting parts of frame members, we placed only four axial spring elements (no diagonal elements).

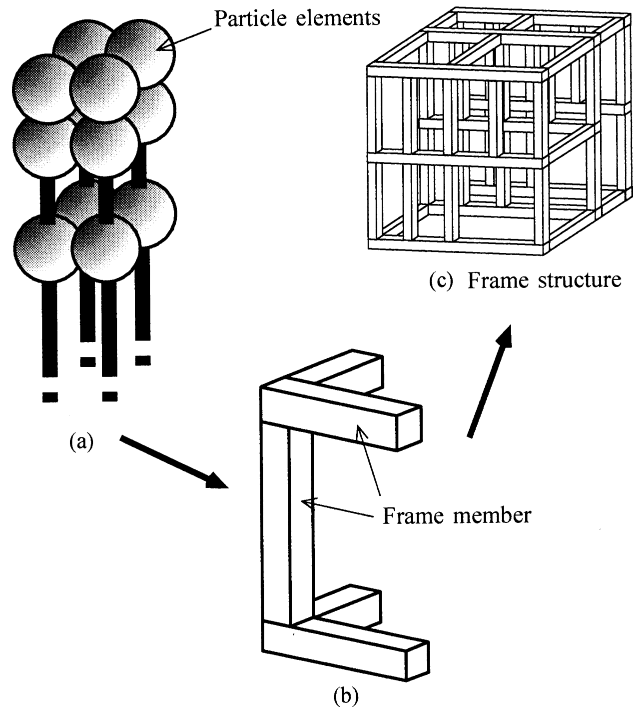

Fig. 2. EDEM elements and units

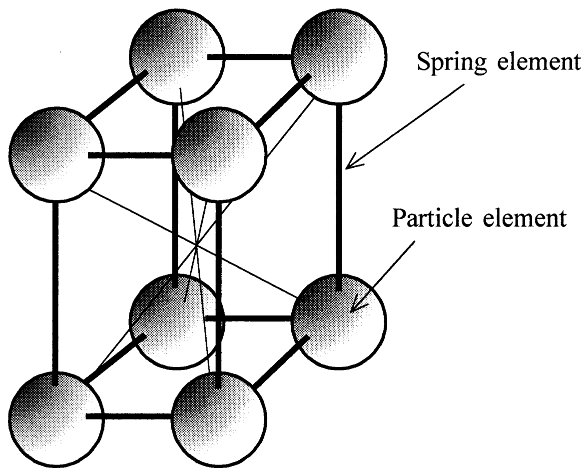

Fig. 3. Configuration of the spring elements in the elementary unit of the EDEM model

Equation of motion

The EDEM calculation is performed under the following theoretical concepts: The motion of a spherical particle element i having the mass m and the moment of inertia I is expressed as follows

$$m\frac{d^2u_i}{dt^2} + C\frac{du_i}{dt} + F_i = 0 \quad (1)$$

$$I\frac{d^2\Phi_i}{dt^2} + D\frac{d\Phi_i}{dt} + M_i = 0 \quad (2)$$

where F_i is the sum of the all forces, including the force of gravity, acting on the particle element; M_i is the sum of the moments acting on it; C and D are damping coefficients; u_i is the displacement vector; and Φ_i is the angular displacement. The time history of u_i and Φ_i can be obtained step by step in the time domain by the numerical integration of these equations. At each step of the calculation the state of the spring elements is checked by the fracture conditions, which are described in the following section. For the EDEM analysis, an element receives forces from all the alive spring elements, and the forces are calculated from the strain of the spring elements. The accelerations of the particle element in x-, y-, and z-directions are then obtained by the following relations, respectively.

$$\frac{d^2x_{it}}{dt^2} = \frac{Fx_{it}}{m} \qquad \frac{d^2y_{it}}{dt^2} = \frac{Fy_{it}}{m} \qquad \frac{d^2z_{it}}{dt^2} = \frac{Fz_{it}}{m} \quad (3)$$

The rotatory acceleration is obtained as follows

$$\frac{d^2\Phi_{it}}{dt^2} = \frac{M_{it}}{I} \quad (4)$$

where x_{it}, y_{it}, and z_{it} are the displacements in x-, y-, and z-directions on particle element i, respectively; Fx_{it}, Fy_{it}, and Fz_{it} are the components of the force acting on particle element i; and M_{it} is the moment acting on it at time t. Velocity increments and displacement increments of the particle elements during a short time period Δt are obtained by numerical integration of these equations. In the DEM or EDEM, the above-mentioned equations of motion are not linked to each other between the different elements, and they are solved as the forward finite difference, which corresponds to propagation of the stress wave. Consequently, large total stiffness matrices as in FEM are not required, and calculation amounts are largely saved.[13] Following this calculation, we can obtain the three-dimensional coordinates of all particle elements consecutively. Thus we can produce every step of the fracturing process in a computer.

Fracture conditions

In the EDEM calculation, the fracture condition is generally defined by the concept of the maximum deformation theory as follows

$$\left(D_{ij} - L_{ij}\right)/L_{ij} > \varepsilon_c \quad (5)$$

where D_{ij} is the distance between particle elements i and j; L_{ij} is the initial distance between them; and ε_c is a constant. In our frame structure model, as the connecting parts are easily broken by shearing deformation between two frame members, the following equation was added

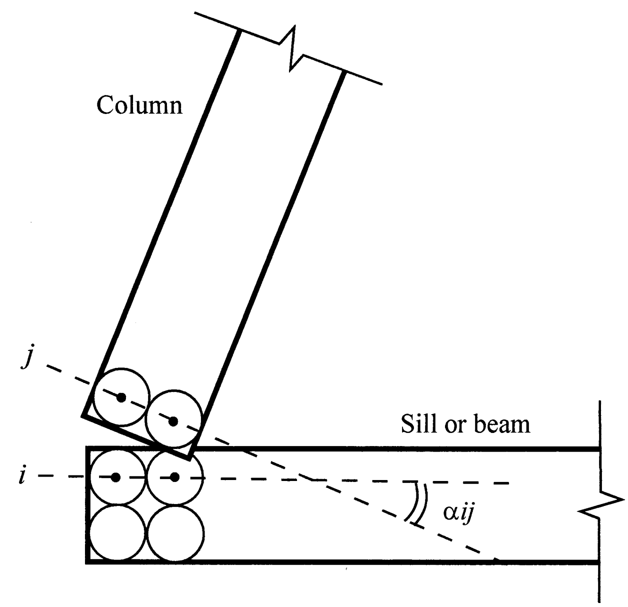

Fig. 4. Definition of α_{ij} used in the fracture condition

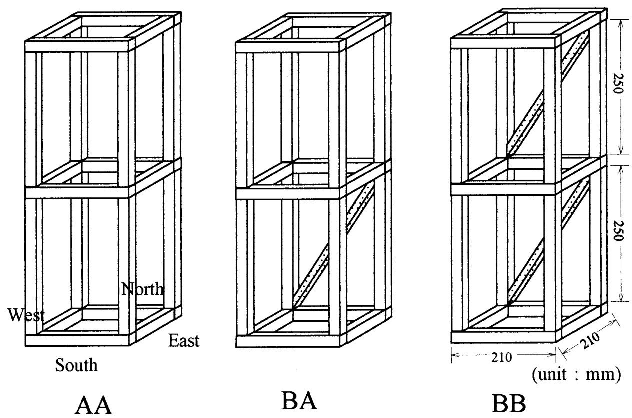

Fig. 5. Configuration of simulated and tested specimens

$$\alpha_{ij} > \alpha_c \quad (6)$$

where α_{ij} is an angle made between lines i and j corresponding to the sill/beam and column, respectively, as shown in Fig. 4; and α_c is a fracture angle. If these fracture conditions are satisfied at any step of the EDEM calculation, four spring elements connecting two particle elements are eliminated simultaneously.

Simulations

Simulated model structures

The simulated model frame structures used in our calculations are shown in Fig. 5. The AA structure assumes a wooden frame structure made with 20 frame members (8 beams, 8 columns, 4 sills). The four directions (north, south, west, east) are indicated in the figure for the convenience of

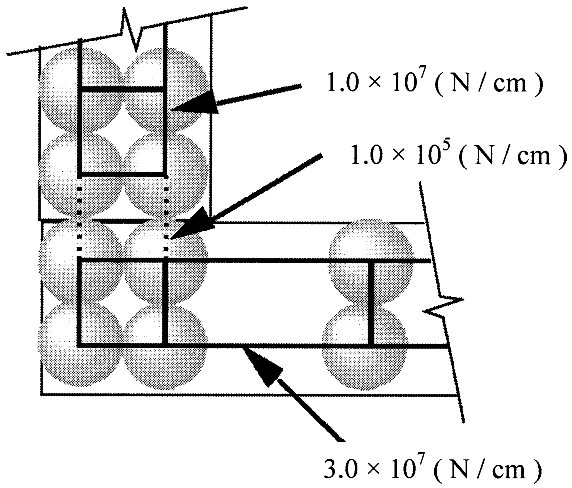

Fig. 6. Modulus of elastic springs

the following explanation. The BA structure has a brace in the northern wall of the first story. This brace is jointed with sill/beam and column. The BB structure has two braces in the northern wall of the first and second stories. In these calculations, the model structures were assumed to be one-ninth scale of the actual size. The sizes of the frame members are shown in Fig. 5. Cross sections of columns, sills, and beams are 20 × 20 mm, and those of braces are 10 × 20 mm. The modulus of spring elements of each frame member was defined to be far larger than that of joint parts. Figure 6 shows the coefficients of the spring elements used here.

Conditions of simulations

Using the above-described model structures, we made our simulations under the following conditions: A mass of 1 kg was added to each beam considering the dead load of the structure. The basement of the model structures (four sills) was moved from east to west at an acceleration rate of 0.3 g ($9.8 \times 0.3\,m/s^2$). The used time period Δt was 10^{-5} ms. The dumping coefficient, which has less effect on the calculated results, was set at 1% of the spring constant provisory. The fracture criteria for Eqs. (5) and (6) are determined to correspond to each simulated case. Here we employed 0.5 for ε_c and $\pi/8$ for α_c. which gave good results that fitted the experimental ones.

Materials and methods

Douglas fir (*Pseudotsuga menziesii* Franco; density 0.45 g/cm^3) was used for the frame members. Joints between the frame members were represented by gummed tapes of 2 × 10 mm. Frame patterns the same as those of the simulated models, shown in Fig. 5, were investigated. The model frame structure was mounted on a sliding basement, which was connected to a 4.2-kg weight by a steel wire (Fig. 7). The dynamic load was applied by dropping this weight mass. Four 0.25-kg metal weights were mounted on the northern and southern beams of both stories. To prevent lateral shifting of the basement, aluminum guides were set along the runaway. Total collapsing processes were filmed by a high-speed video camera (NAC: HSV-500).

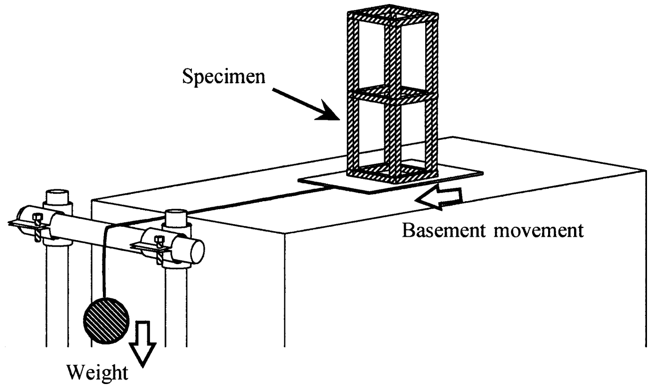

Fig. 7. Test equipment for dynamic loading

Results and discussion

Figure 8 shows the collapsing process of the AA structure, which has no shear wall, obtained by our simulation. Following the law of inertia, the movement of the second story delays until that of the basement members. Thus the first-story structure leans gradually; and the spring elements of two joint parts of the upper southwest corner and lower northeast corner disappear at 80 ms, satisfying the angular fracture condition. Then, at 100 ms, six other joint parts of the first story are broken. Finally, all columns of the first story are separated from the beams and sills, and the first story collapses totally, with the second story falling on it. The results of the corresponding experiment are shown in Fig. 9. The results were similar to those of the simulated results.

Equipped with a brace in the northern wall of the first story, the BA structure behaves differently from the AA structure, as shown in Fig. 10. The northern wall of the first story is hardly deformed, whereas its southern wall and the northern wall of the second story are extensively deformed. As the result, the west- and east-side beams lean markedly, and the first breaking of the spring elements occurs at the northern ends of these beams. Then the joints of the columns in the southern wall of the first story and northern wall of the second story reach the fracture condition. All the walls except for the northern wall of the first story are broken at 100 ms. Figure 11 shows the experimental results of the BA structure. The total collapsing process coincided well with our EDEM simulation.

Figure 12 shows the collapsing process of the BB structure. In this case, the southern walls of the first and second stories have braces. Both northern walls deform little, whereas the southern wall of the first story deforms markedly. At 70 ms, the west- and east-side beams of the

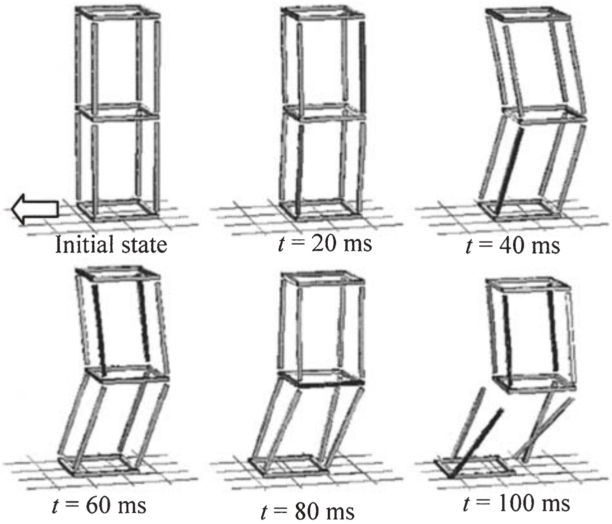

Fig. 8. Collapsing process of the AA structure during the simulation

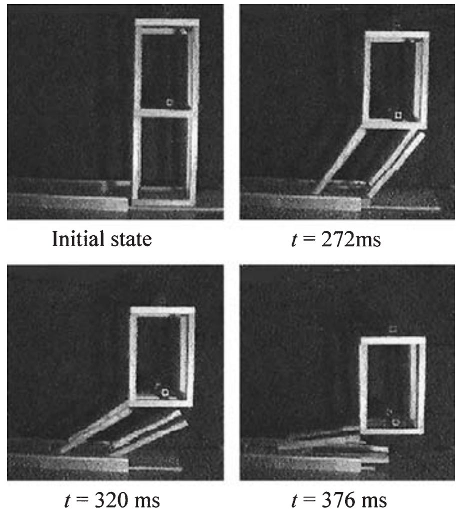

Fig. 9. Collapsing process of the AA structure during the experiment

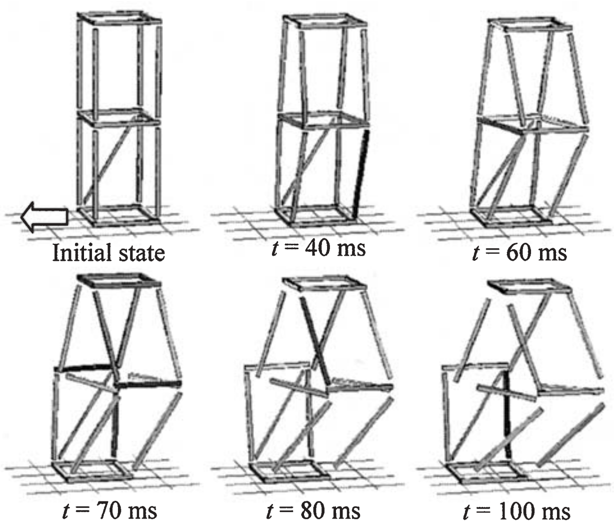

Fig. 10. Collapsing process of the BA structure during the simulation

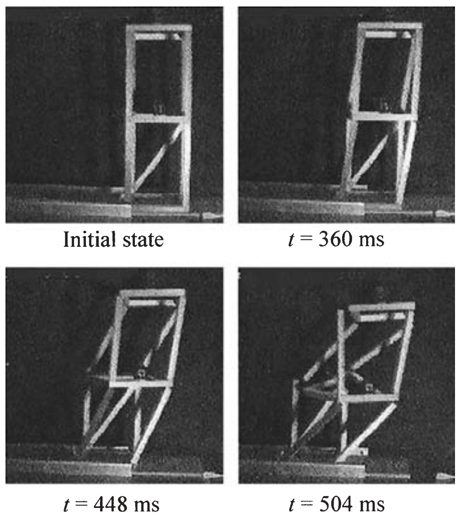

Fig. 11. Collapsing process of the BA structure during the experiment

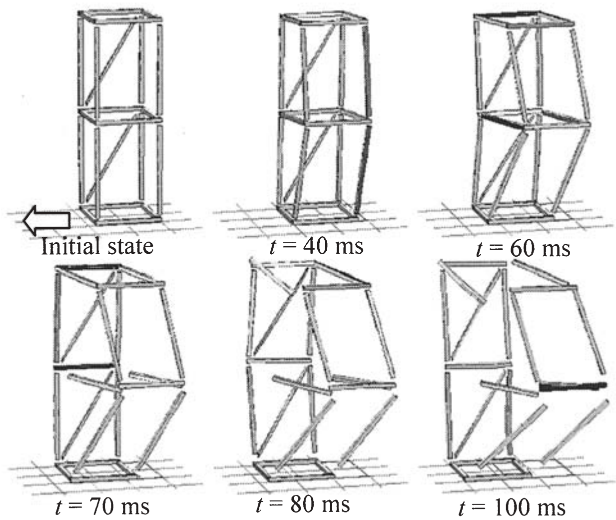

Fig. 12. Collapsing process of the BB structure during the simulation

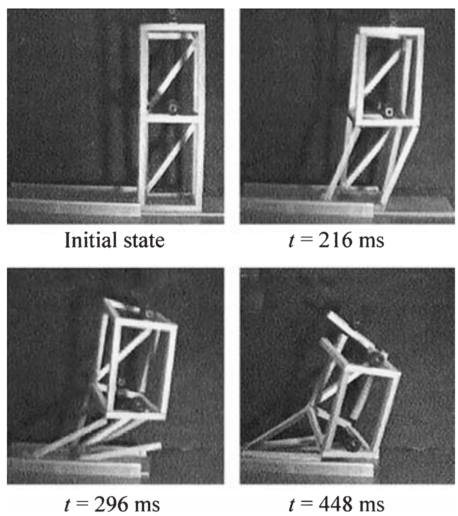

Fig. 13. Collapsing process of the BB structure during the experiment

first story lean markedly, and the first breaking of the spring elements occurs at the northern ends of these beams. At 100 ms the southern wall of the first story crashes, and consequently the southern wall of the second story falls. The northern walls survive these processes. Figure 13 shows the experimental results of the BB structure. In this case, the deformation of the southern walls is similar to the simulated results, but there are several differences in the collapsing processes between the experimental results and our calculation. Perhaps the estimation of the parameters of the spring elements in our calculation did not match well those of the experimental model.

The total time scale did not coincide for the simulations and experiments, but the simulated result by our method corresponded well with the experimental results qualitatively. Therefore, it is suggested that the collapsing process of wooden structures with various configurations of shear walls can be predicted by our new method. However, the quantitative outcome is essential for the simulation of actual-size structures, so our calculating method must be improved to realize the quantitative simulations from now on.

Conclusions

The collapsing process of wooden-frame structure models under dynamic loading was investigated by the newly developed numerical program based on the EDEM. Using this method, it was demonstrated that the frame models with different shear wall configurations collapse in different ways. Simulated results corresponded well with the experimental results under similar conditions. Our new method proved to be promising for measuring future aseismatic designs, but further improvement is required to realize a quantitative simulation.

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