Motion analysis of furniture under sine wave excitations

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ABSTRACT: Improperly secured furniture, especially on the upper floors of high-rise buildings under long-period ground motion, can become dangerous objects for human life. Many tumbled furniture such as chairs and tables in schools could become fatal obstacles that prevent children from evacuating. The objective of this research is to develop an effective numerical code to analyze the motion behaviors of furniture subjected to seismic excitations. The numerical code is constituted based upon the adaptively shifted integration (ASI) – Gauss technique, which is a finite element scheme that provides higher computational efficiency than the conventional code. This code is able to analyze dynamic behavior with strong nonlinearities which are related to phenomena such as fracture and contact. In this paper, the frictional contact between objects was fully considered by employing a sophisticated penalty method. A basic evaluation was carried out by comparing the results of certain experiments with analyses of the motion behaviors of steel cabinets excited by sine waves. It should be emphasized that the present code is able to evaluate the motion behaviors of the furniture as well as the deformations and stress distributions, which is one of the advantages of using a finite element scheme.

1 INTRODUCTION

Improperly secured furniture, especially on the upper floors of high-rise buildings under long-period ground motion, can become dangerous objects for people. Many tumbled furniture such as chairs and tables in schools could become fatal obstacles that prevent children from evacuating. To investigate the motion behaviors of furniture under various conditions, the E-defense of NIED carried out several experiments using a three-dimensional full-scale shaking table and obtained useful information (E-defense 2009). In parallel, the E-simulator project is aiming to develop an effective simulator for investigating the motion behaviors of such furniture under a broader set of conditions. The discontinuous element method (DEM) (Cundall 1971) may be useful for this purpose; however, the mechanical behaviors of the constituent materials of the structural components may not be well examined.

The main objective of this research is to develop a low-cost, highly accurate numerical code to analyze the motion behaviors of furniture, without neglecting the elasto-plastic and damage behaviors of structural components. To model the motion behavior of furniture, a contact algorithm using the penalty method is implemented into a finite element code based upon the adaptively shifted integration (ASI) – Gauss technique (Lynn & Isobe 2007). The numerical results are validated by comparing the motion behaviors of steel cabinets with experiments performed on an excitation table.

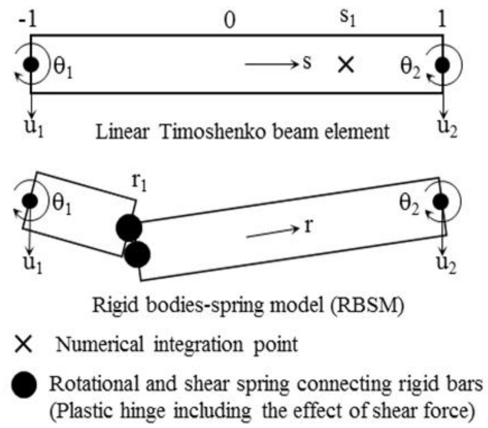


Figure 1. Linear Timoshenko beam element and its physical equivalent.

2 NUMERICAL METHODS

2.1 *ASI-Gauss technique*

In this paper, the numerical analyses are carried out using a finite element code based upon the ASI-Gauss technique with linear Timoshenko beam elements. Figure 1 shows a linear Timoshenko beam element and its physical equivalence to the RBSM. As shown in the figure, the relationship between the locations of the numerical integration point and the stress evaluation point where a plastic hinge is formed is expressed as (Toi 1991):

$$r = -s \tag{1}$$

Here, s is the location of the numerical integration point and r is the location where stresses and strains are evaluated. The variables s and r are nondimensional quantities that take values between -1 and 1.

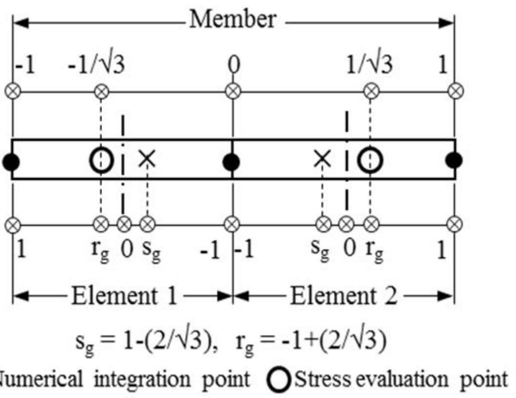


Figure 2. Locations of numerical integration and stress evaluation points.

In the ASI-Gauss technique, the numerical integration point is shifted adaptively according to Eq. (1) when a fully plastic section is formed within an element, to form a plastic hinge exactly at that section. By doing so, the plastic behavior of the element is simulated appropriately, and the converged solution is achieved with a minimum number of elements per member. When the plastic hinge is unloaded, the corresponding numerical integration point is shifted back to its normal position. Here, the normal position means the location where the numerical integration point is placed when the element acts elastically. Two consecutive elements forming a member are considered as a subset, as shown in Figure 2, and the numerical integration points of an elastically deformed member are placed such that the stress evaluation points coincide with the Gaussian integration points of the member. This means that stresses and strains are evaluated at the Gaussian integration points of elastically deformed members. Gaussian integration points are optimal for two-point integration, and the accuracy of the bending deformation is mathematically guaranteed (Press et al. 1992). The scheme takes advantage of two-point integration while using one-point integration in actual calculations. More details on the code can be found in previously published papers (Lynn & Isobe 2007, Toi & Isobe 1993).

2.2 *Contact algorithm considering friction*

To realize various contact phenomena during seismic excitation, frictional contact between objects was considered in this paper with the penalty method and by considering dynamic friction. Figure 3 shows the subjected forces and the geometrical relations between two elements when they approach one another with a relative velocity $\boldsymbol{v}$. Once the current distance l between the central lines of two elements becomes shorter than the mean value L of the member widths of the elements, the penalty force vector $\boldsymbol{F_P}$ shown below is assumed to act in the normal direction of the contact plane.

$$F_P = \alpha\left(1-\frac{1}{L}\right)^q \frac{v_N}{\|v_N\|}, \quad where \quad (l \le L) \tag{2}$$

Here, α is a penalty coefficient, q is a penalty index, and $\boldsymbol{v_N}$ is the normal direction component of the relative velocity $\boldsymbol{v}$, respectively. When the value of α is 50 kgf and q takes on various values, the penalty forces along the contact depth l/L are distributed as shown in Figure 4.

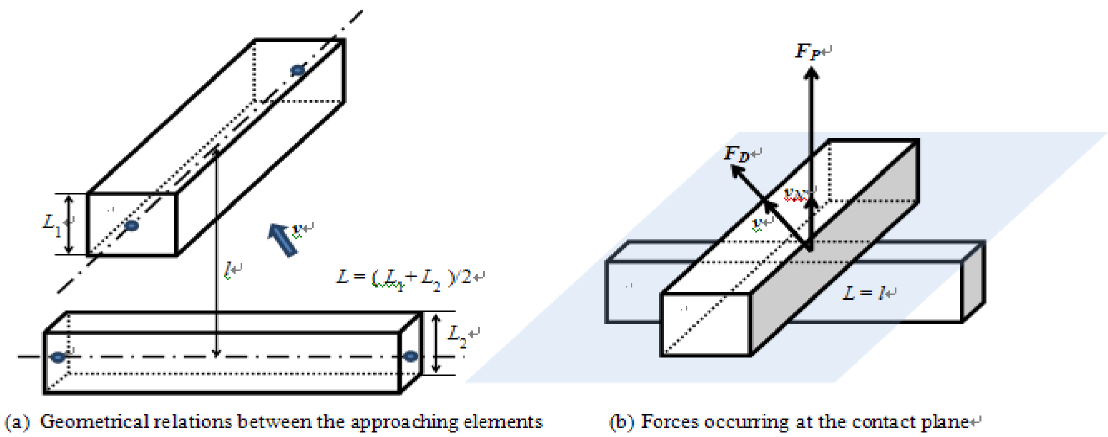


Figure 3. Subjected forces and the geometrical relations between the elements.

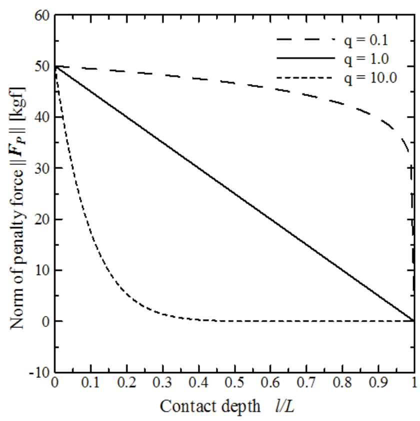
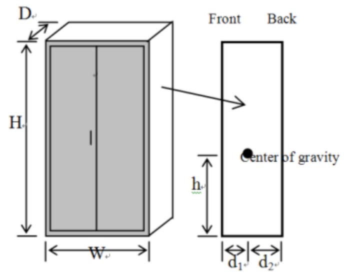


Figure 4. Penalty force as a function of contact depth.



Sizes [cm]	H=179 W=88 D=38
Position of the center of gravity [cm]	h=87 d_1=16 d_2=22
Weight [kg]	41

Figure 5. General sizes and properties of steel cabinets.

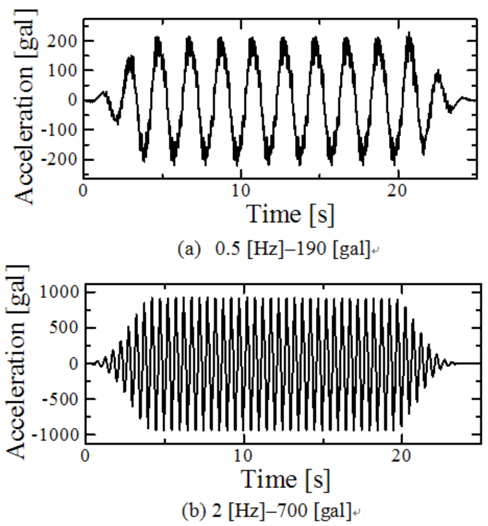


Figure 6. Input sine waves

Then, in this paper, a frictional force vector $\boldsymbol{F_D}$ is assumed to act not only in the tangential direction of the contact plane but also in the normal direction, as shown below.

$$F_D = \mu\alpha(1-\frac{1}{L})^q \frac{v}{\|v\|}, \quad where \quad (l \le L) \tag{3}$$

Here, μ is a dynamic friction coefficient. The component in the normal direction acts as a damping force along the contact depth and contributes to increasing the numerical stability.

3 MOTION ANALYSIS OF OVERTURNING FURNITURE

3.1 *Numerical model and analytical conditions*

Some motion analyses were carried out on furniture and compared with the experimental results (Kaneko et al. 2004). Two steel cabinets, with properties as shown in Fig. 5, are subjected to two sine waves of different frequencies and maximum acceleration values. The selected input waves are (a) a long-period wave of 0.5 [Hz]–190 [gal], and (b) a short-period wave of 2 [Hz]–700 [gal], as shown in Fig. 6. In case (a), one cabinet is set upright at the center of an excitation table, and the other one is also set upright, beside a wall. In case (b), one cabinet is laid down on the floor at the center of the excitation table, and the other one is set upright, beside a wall. We fixed the parameters as α =50 kgf, q=1 and μ =0.6 for the dynamic friction coefficient between the cabinets and the floor or the wall. The cabinet frame, the floor and the wall are modeled with two linear Timoshenko beam elements per member, and the center of gravity of the cabinet model is adjusted by varying the density of the elements.

3.2 *Results*

Figure 7 and Fig. 8 show the comparison of the motions obtained by the experiments and the analyses. The overturning durations and the behaviors of the cabinets agree well in both cases. Each analysis required approximately 6 hours of simulation time using a personal computer (CPU: 2.0 GHz Xeon).

4 CONCLUSIONS

The numerical code and the frictional contact algorithm developed in this paper succeeded in simulating the motion behaviors of furniture subjected to sine wave excitations. However, the motion behaviors of the models in this paper did not contain any yielding or damage phenomena in the structural elements. Our next plan is to investigate the motion behaviors of colliding furniture that may require more detailed modeling of the constituted materials.

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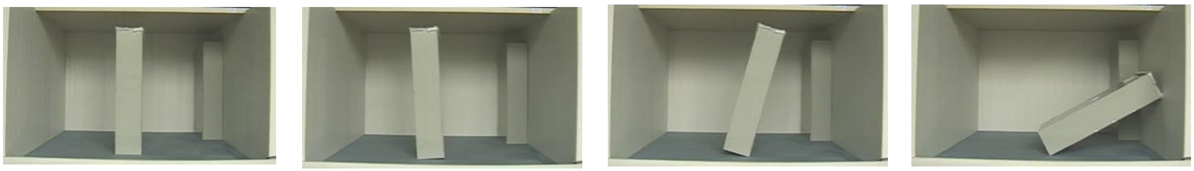
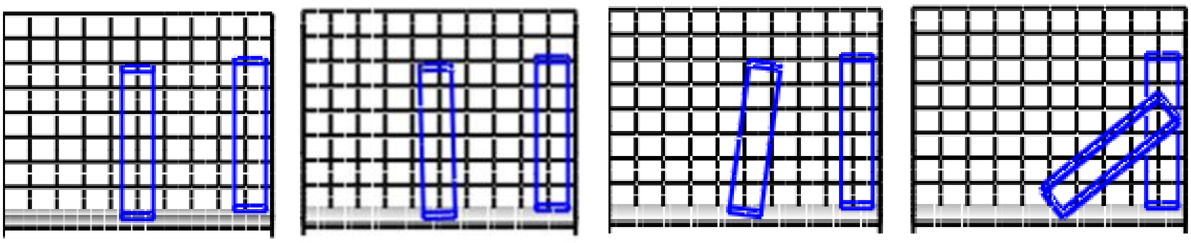


0 [s] 4 [s] 5 [s] 6 [s]

(a)Experimental result



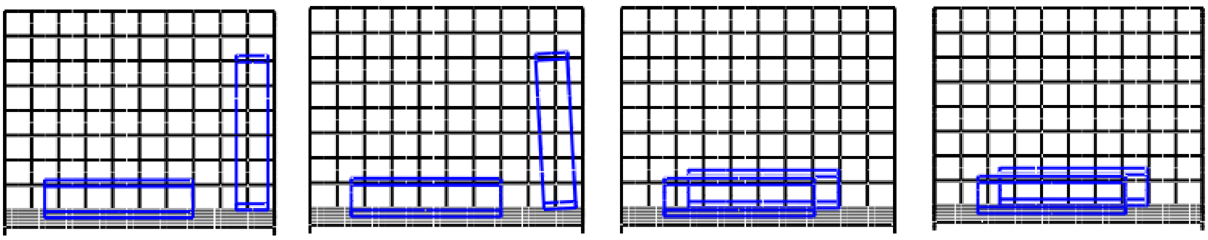
0 [s] 4 [s] 5 [s] 6 [s]

(b) Numerical result

Figure 7. Comparison of experimental and numerical results (0.5 [Hz]–190 [gal]).

0 [s] 4 [s] 6 [s] 16 [s]

(a)Experimental result



0 [s] 4 [s] 6 [s] 16 [s]

(b) Numerical result

Figure 8. Comparison of experimental and numerical results (2 [Hz]–700 [gal]).