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RESPONSE OF INTERIOR RIGID BODY ASSEMBLIES TO DYNAMIC EXCITATION

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ABSTRACT

Whenever an earthquake occurs in a populated area there is a possibility that there will be damage inflicted upon engineered building structures, as well as to their exteriors. Although there are examples underlining the contrary, as a consequence of the development of design and construction techniques for civil engineering structures, in most earthquake events there is a decreasing probability of excessive damage to the primary structures. Yet, there is considerable hazard for the inhabitants due to the displacement of furniture and other objects of interiors. As the highly non-linear response of rigid body assemblies to dynamic excitation would be very complex analytically to follow, in order to allow for a deeper insight into the problem, the authors ventured upon a quest for, and the justification of, the applicability of the Distinct Element Method (DEM) to compute response numerically. Based on the DEM there was developed a software for the general public to become more acquainted with the phenomena that directly concern them. This paper is devoted to a brief discussion of the milestones in the justification of the applicability of the DEM, and the introduction of the above mentioned educational software.

KEYWORDS

Rigid bodies; dynamic excitation; interior objects; Distinct Element Method; shaking table experiments; educational software.

INTRODUCTION

The photo in Fig. 1. shows an interior with overturned furniture after the Kushiro (Japan) earthquake in 1993. The phenomenon of overturning has been a subject of research for somewhat longer than a century now. Many scientists and engineers expanded time and effort over the quest for a method to predict overturning of rigid rectangular bodies. The first publications were those of Milne (1881 and 1885) and Perry (1881). Lower limits of maximum acceleration and velocity of a single pulse required to overturn a single rectangular block on a rigid floor were introduced. Their study and results are very fundamental and have not been largely transcended to this day. Housner (1963) argued that the aforementioned criteria may not be applied in the case of earthquake

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Fig. 1. Interior with overturned furniture after the Kushiro-Oki earthquake of 1993.

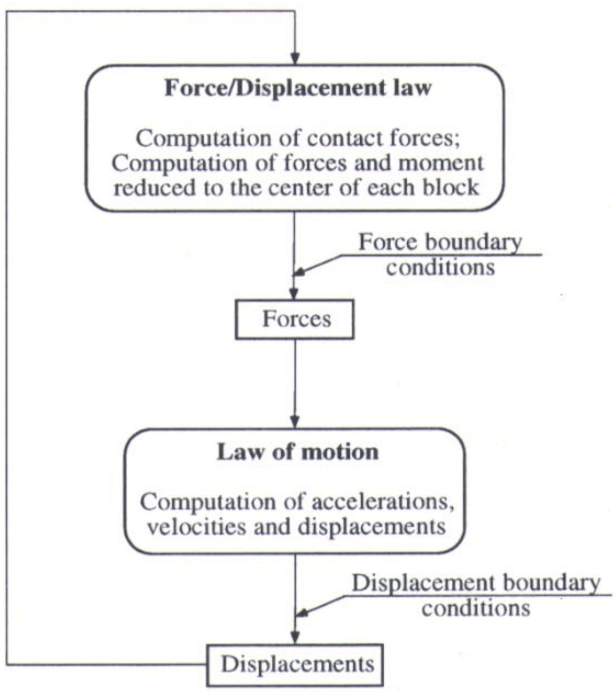

Fig. 2. The flow of DE computation.

excitation because the time period required for overturning by a single pulse will not be allowed for before a subsequent impact during an earthquake. Yim (1980) presented a very insightful study of rocking and overturning and concluded that deterministic estimates of overturning may not at all be reliable. Ishiyama (1982) suggested a correction to Milne's velocity criterion. Manos (1990) published his experimental study on solid, sliced body assemblies to base excitation. An analytical study of the response of two-block assemblies was given by Psycharis (1990). This was the first analytical study of not only one block on a rigid floor. The procedure showed very complicated as the equations of motion and energy dissipation had to be formulated for every possible mode of response. The authors of this paper sought a numerical method that is applicable to quite

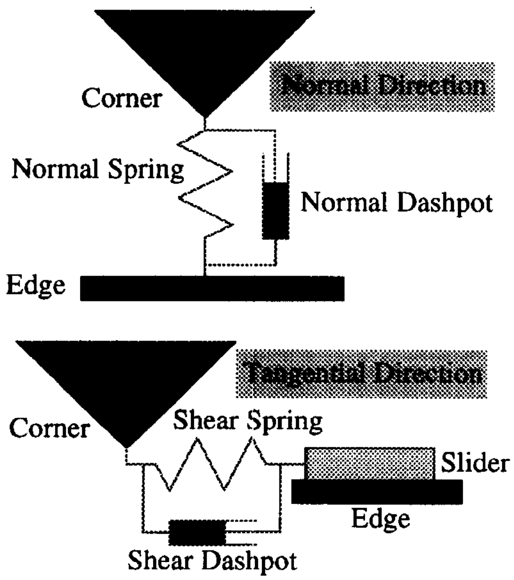

Fig. 3. The distinct element model.

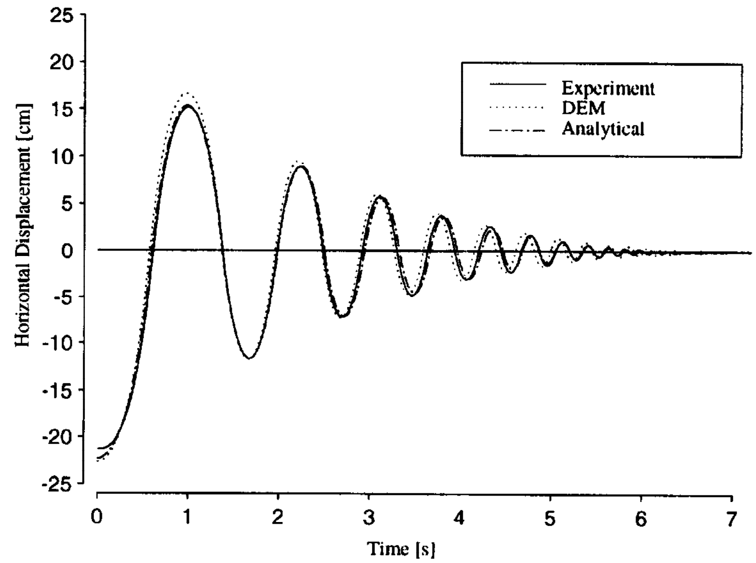

Fig. 4. Time histories of free vibration of a rigid block.

irregular assemblies of rigid bodies and boundary conditions. This method, the DEM, is briefly introduced and proven applicable to the problem of overturning of rigid body assemblies under base motion in the following pages.

BRIEFLY ABOUT THE DISTINCT ELEMENT METHOD

The method of calculation (Fig. 2.) is essentially similar to that described by Cundall (1971). In the two dimensional DE program used for the computation of behaviour of assemblies of rigid blocks, there is no restriction of block shapes and no limitation to the magnitudes of translational and rotational displacements. All deformations are assumed to occur at the surfaces of blocks; at edge-to-corner contacts (Fig. 3.). The equilibrium of two edges that are in contact is established by the fact that the forces at the two corners adjust themselves to be in the ratio required for equilibrium. Forces arise due to deformation. A change in displacement results in a change in force stored for a particular contact. Within one step of calculation, incremental and total forces, acceleration, velocity, and finally displacement, are computed for all of the elements.

SHAKING TABLE EXPERIMENTS

A series of shaking table tests were conducted in the Chiba Experimental Station of The University of Tokyo using a two-directional (horizontal and vertical) shaking table. Parallelepipeds glued from thin wooden plates were used for specimens. The solid, composite material the blocks were made of provides that they can be regarded as rigid bodies. To monitor the motion of the specimens, two accelerometers for measuring horizontal and vertical acceleration were attached to each block. To establish the occurrence of rocking and overturning, acceleration data were compared with time histories of angle of rotation from the DE simulation.

Shaking tests on different combinations of blocks were conducted using harmonic excitations. In this paper, due to limitations of space, only one of the many studied examples will be presented. For a comprehensive justification of applicability the reader will refer to Winkler et al. (1995).

Columns, composed of two blocks (h=50 cm, b/h=0.3), were tested under different boundary conditions in order to confirm how accurately the numerical simulation follows the highly non-linear response of complicated

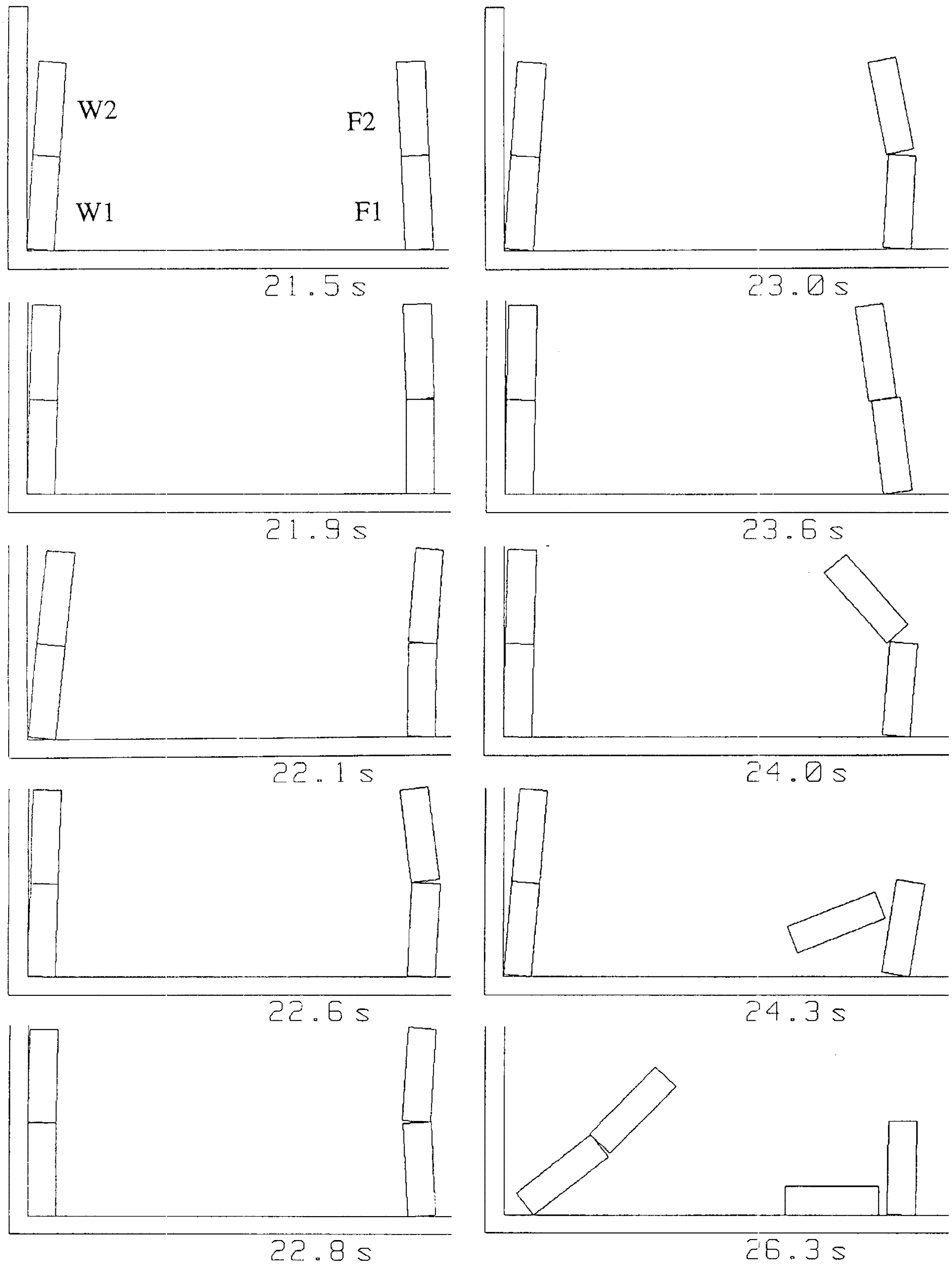

Fig. 5. Characteristic frames of the animation of the response of two-block columns - one freely standing and one interacting with a wall - under a 3 Hz sinusoidal base motion.

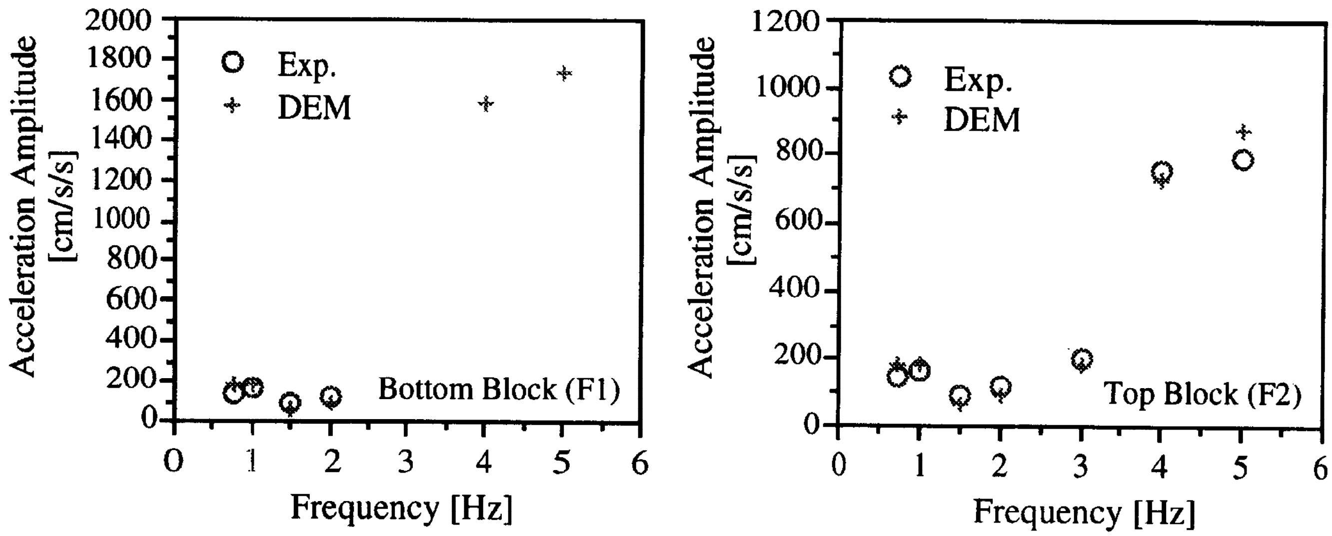

Fig. 6. Criteria of overturning for a freely standing column of two blocks.

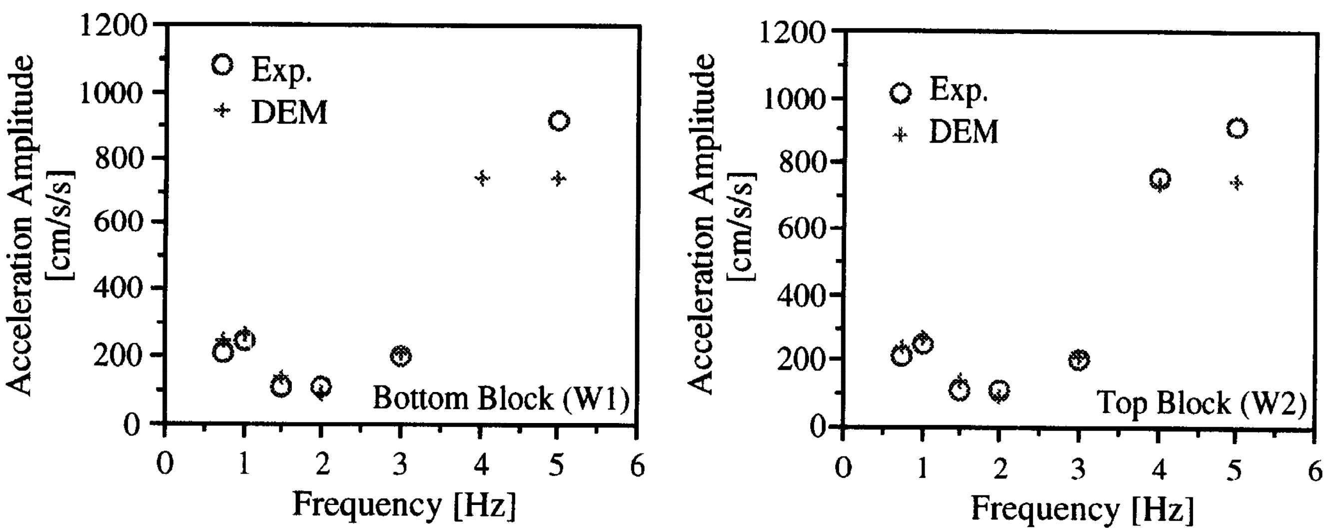

Fig. 7. Criteria of overturning for a column of two blocks interacting with a wall.

assemblies. The simplest assembly tested was a two block column in which a block was placed on top of another. It was similar to that that the behavior of which was analytically studied by Psycharis (1990). To make the response more non-linear and therefore more complicated, the above column was also tested set next to a wall that was firmly attached to the shaking table. The example thus created resembles that of bookshelves and cupboards that respond to ground motion in interaction with a wall. The two-block assemblies were tested under harmonic base motion of frequencies from 0.75 Hz to 5.0 Hz.

NUMERICAL SIMULATION

Stiffness, damping and friction parameters of the DE contact model were estimated as follows. A wave propagation experiment was carried out to measure wave propagation velocities in the specimens. According to Meguro et al. (1988) normal and shear spring constants were then computed. The energy dissipation at contacts was represented by velocity proportional damping. To identify an appropriate damping constant, a free vibration

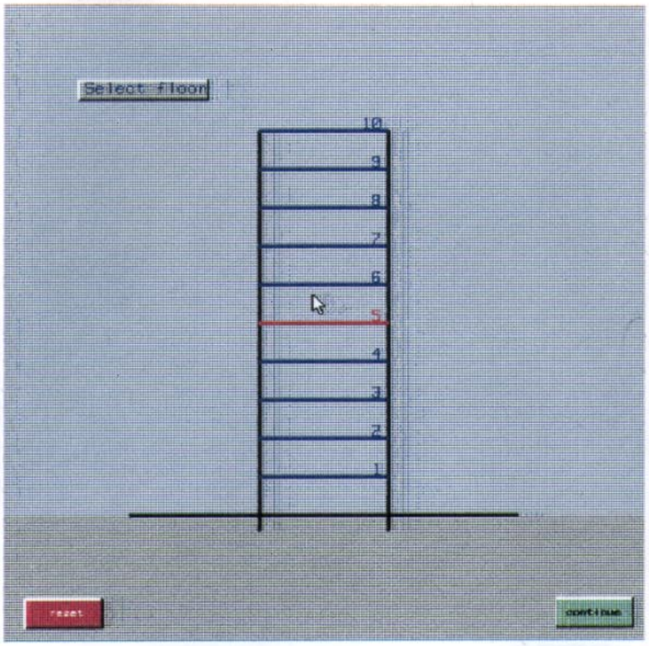

Fig. 8. Selecting the floor on which the interior is located.

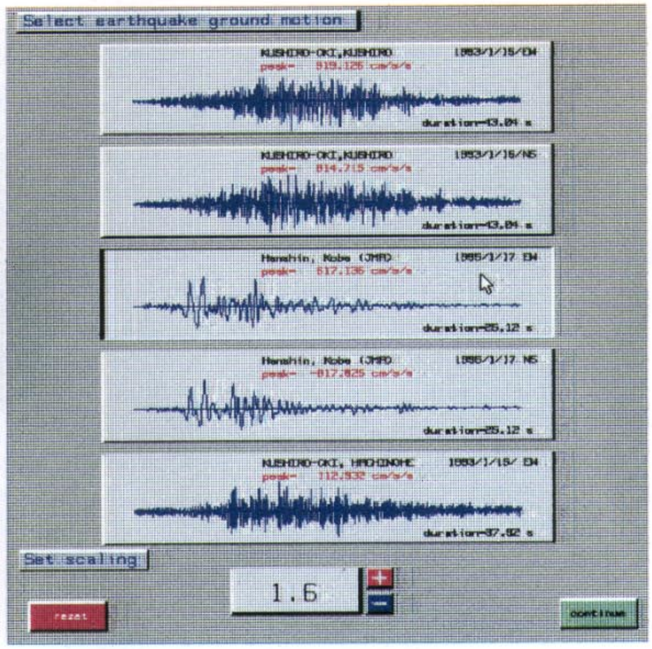

Fig. 9. Selecting the earthquake motion.

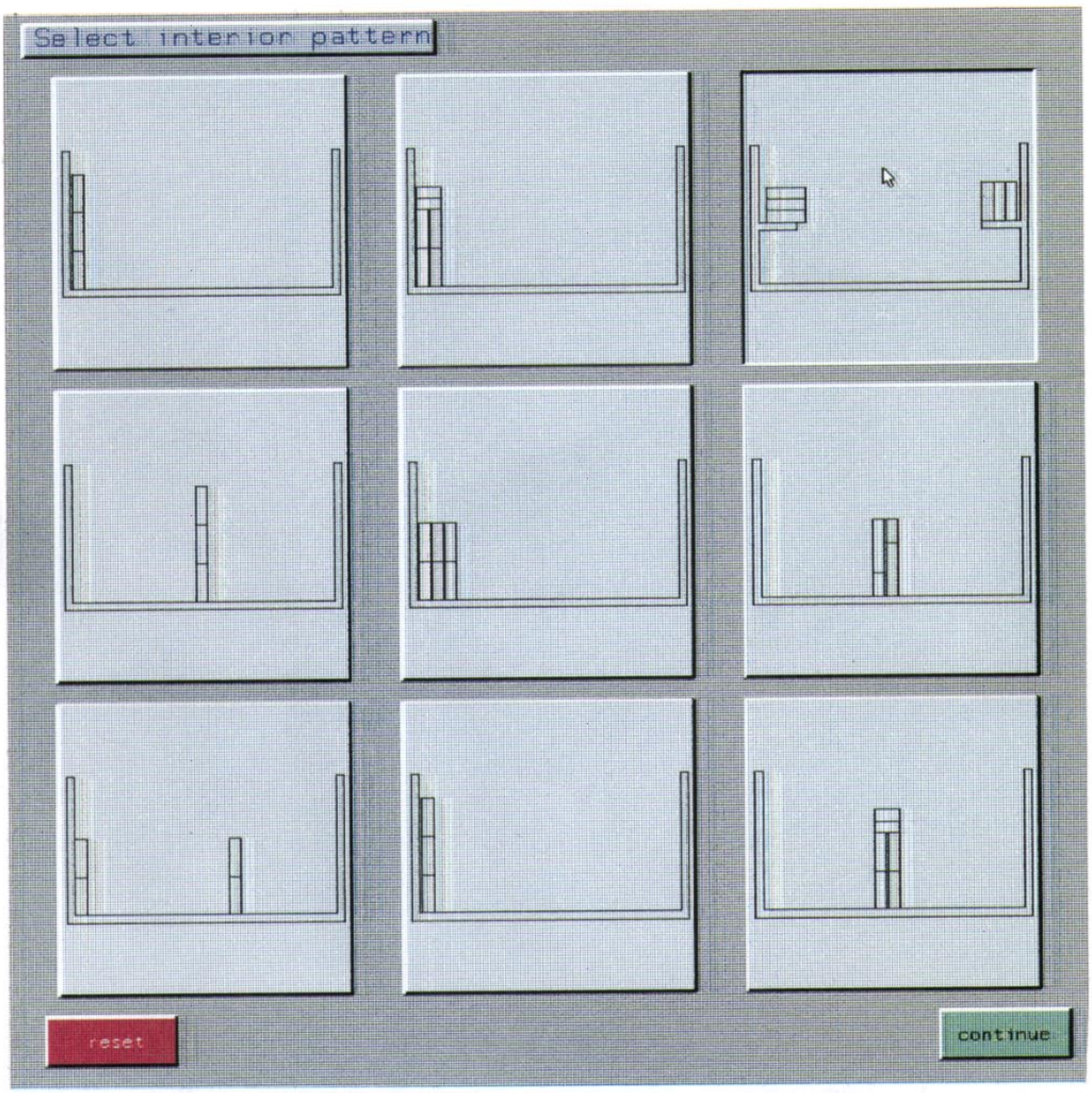

Fig. 10. Selecting the interior pattern.

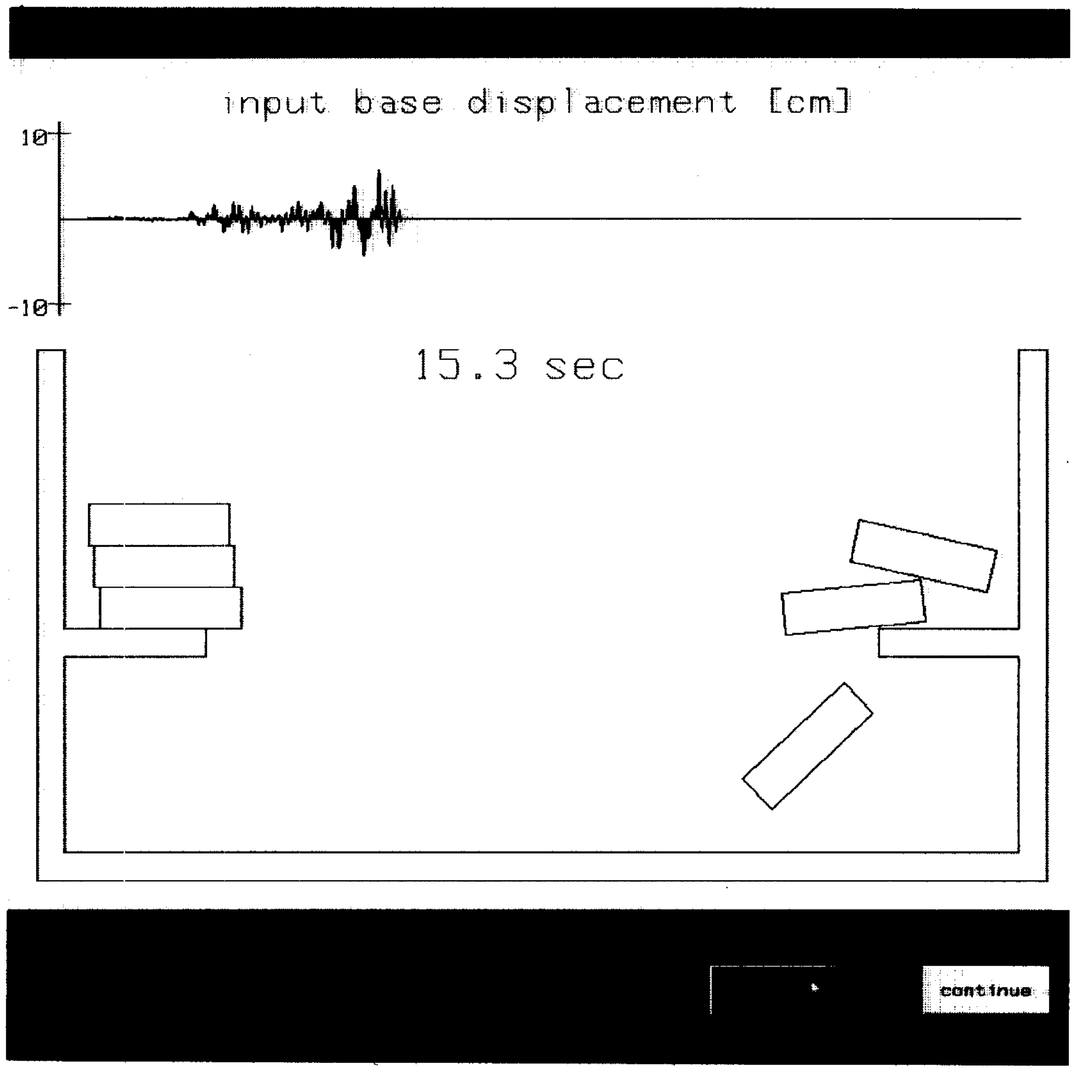

Fig. 11. Real-time animation of the response of the interior.

test of a single block was performed and the time histories of horizontal displacement were fitted by adjusting the damping coefficient (Fig. 4.). The numerical simulation of the shaking table tests was conducted using input base motions recorded in the experiments. A number of characteristic frames of the response of the two-block columns to a 3 Hz sinusoidal base motion of linearly increasing amplitude are shown in Fig. 5., and criteria of overturing with respect to excitation frequency versus input acceleration amplitude are shown in Fig. 6. and Fig. 7. The DE model seems to be able to follow the interactive, highly non-linear response of these complex assemblies quite accurately. Discrepancies in overturning acceleration amplitudes at higher frequencies may be attributed to an out of plane response of the specimens. In those cases, even though the columns would lose stability, their overturning occurred after a period of out of plane response. The DEM proved applicable to the problem of overturning of rigid body assemblies due to dynamic excitation.

WHAT WILL BECOME OF YOUR INTERIOR IN CASE OF AN EARTHQUAKE?

On the basis of the agreement in several examples, the authors are introducing a software through the use of which the above question can quite simply be answered. The software combines the computation of earthquake response of a multi storey structure with DE simulation of the response of interior objects. The system is very user friendly and simple to operate; its usage does not require special qualification of any sort whatever. Anyone of the general public may sit down in front of a computer and simply by clicking with the mouse can select a set of location (Fig. 8.), earthquake motion (Fig. 9.) and interior (Fig. 10.). As the result of computation the user will be presented with a real-time animation of the response (Fig. 11.) of the chosen interior to the computed input motion of the specified floor. Through the interiors shown in Fig. 10. some of the most typical arrangements of furniture and other objects in offices and homes are suggested. It is not uncommon that due to space constraints offices are subdivided by bookshelves and compartments of other sorts, placed on top of one another. Such positioning would constitute potential hazard for the employees working at desks within the subdivided space. The bottom right example and the one just above it show possible common arrangements of furniture of that fashion. The top left interior is another classic example; it depicts shelves laden in two different ways. Through this elementary pattern, awareness to the dangers represented by improper storage can be raised.

It would seem advisable that the interior designer should refer to predictions offered by this software prior to implementing an idea for an interior. Naturally, the arrangements in Fig. 10. are only examples, the user may create his own interior to analyse.

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