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SIMULATION OF COLLAPSE OF STRUCTURES DUE TO THE 1995 GREAT HANSHIN EARTHQUAKE

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ABSTRACT

At 5:46 a.m. (local time) on January 17, 1995, the Great Hanshin (Hyogo-Ken Nanbu or Kobe) earthquake hit the Hanshin-Awaji area, Japan. The damage due to this earthquake was the worst earthquake disaster in Japan since the 1923 Great Kanto earthquake. Over 100,000 houses and buildings collapsed and many modern civil infrastructures such as elevated bridges of highways and railways, and port facilities, etc. were also heavily damaged. In addition, fires broke out razing many houses after the quake. The death toll was more than 6,300 including deaths due to various problems following the earthquake. Unfortunately, most deaths were caused due to collapse of structures. To mitigate casualties due to earthquakes, it is important to study the mechanism of collapse of structures during earthquakes. In this study, using the Extended Distinct Element Method (EDEM), which is applicable to both a composite and continuous medium, and a perfect discrete one, the collapse mechanism of structures during the 1995 Great Hanshin earthquake is studied. Although the phenomena treated in this study were difficult to be simulated by the conventional methods such as the finite element method, the numerical results obtained agree well with the actual earthquake damage.

KEYWORDS

Great Hanshin earthquake; Hyogo-Ken Nanbu earthquake; Kobe earthquake; earthquake damage; structural damage; distinct element method; extended (or modified) distinct element method; fracture analysis; computer simulation; casualties.

INTRODUCTION

To mitigate casualties due to earthquakes, it is important to study the mechanism of collapse of structures during earthquakes. The Great Hanshin earthquake on 17 January, 1995 caused over 100,000 collapsed houses and buildings, many heavily damaged civil infrastructures, and more than 6,300 deaths. Most of the deaths were due to collapse of structures.

To assure the safety of the general public in the event of future earthquakes, it is vital to analyze the collapse of structures. The process which is used in analyzing the behavior of structures in a collapse, addressing the problems such as, "Where and how do they undergo collapse?", "Is the time of collapse short or long?", "How far would the fragments of structural members fly and/or move in the process of collapse?", and "Would the collapse of structures be partial or overall?", is expected to greatly reduce the domains of structure collapse behavioral uncertainties. It is hoped that the knowledge of engineering concerned with collapse of structures will pave way in bringing forth approachs which could clarify these uncertainties. For example, we may undertake such architectural designs which allow partial structural collapse but prevent complete collapse. The means of such an analysis at present is the Extended (or Modified) Distinct Element Method (EDEM, MDEM) (Iwashita and Hakuno, 1990, Meguro *et al.*, 1988, Meguro *et al.*, 1991) which were developed from the distinct element method (Cundall, 1971).

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In this study, using the EDEM, the mechanism of collapse of structures during the 1995 Great Hanshin earthquake is studied by simulating various modes of collapse process reported after the quake.

EXTENDED DISTINCT ELEMENT METHOD

Although the conventional distinct element method (DEM) used in geotechnical engineering has proved very useful, only a few applications are heard in other media (Meguro and Hakuno, 1989a, Meguro and Hakuno, 1992, Meguro and Hakuno, 1994). The use of DEM was extended to the fracture analysis of structures, usually analyzed only by the methods based on continuum equations such as the FEM. The EDEM was originally developed by the research group including the first author of the paper. A computer algorithm has been written which can be used both for geotechnical engineering and for various other media as well. This method maintains continuity of the elements because it includes the additional spring called pore-spring or joint-spring which represents the effects of the material surrounding the elements. **Figure 1** shows the EDE modelling.

The equations of motion of an element, *i*, having the mass, ***mi***, and the moment of inertia, ***Ii***, are

$$mi \cdot d^2u/dt^2 + Ci \cdot du/dt + Fi = 0 \tag{1}$$

$$Ii \cdot d^2\phi/dt^2 + Di \cdot d\phi/dt + Mi = 0 \tag{2}$$

in which ***Fi*** is the sum of all the forces acting on the element; ***Mi*** the sum of all the moments acting on it; ***Ci*** and ***Di*** the damping coefficients; ***u*** the displacement vector; and ϕ the rotational displacement.
The time histories of ***u*** and ϕ are obtained step-by-step in the time domain by the explicit numerical integration of equations (1) and (2).

As forces acting on an element are of two kinds, ***Fi*** and ***Mi*** are expressed as

$$Fi = Fie + Fip + mi\,(g+\alpha) \tag{3}$$

$$Mi = Mie + Mip \tag{4}$$

where ***Fie*** is the sum of forces from all the elements in contact; and ***Fip***, from all the material surrounding it. ***Mie*** and ***Mip*** are the sums of all the moments from all the elements in contact and from all the material surrounding it respectively. These forces are obtained from the deformations of the element and pore-springs (joint-springs) set in the normal and tangential directions. In equation (3), ***g*** is the acceleration due to gravity and α is the external acceleration acting on it. As the fracture criterion of the pore-spring, a critical tensile strain (β) is specified in the normal direction, and Coulomb's equation is used in the tangential direction.

A new concept regarding the application of the EDEM is also proposed in this study: the EDEM can be taken as an extended lumped mass system, the field of application of which is extended to the discontinuous media, unlike the standard lumped mass system which is applicable only to the continuous media.

The EDEM is a conceptual model realized with a unique idea incorporated, wherein elements are each recognized as a unitary element of motion, a key to solve the equation of motion, and an interaction among elements is regarded as a spring action. In another aspect, the EDEM is taken as a lumped mass system, a subsystem of the composite, multi-degree-of-freedom (MDOF) system. Reference will now be made to "What is the most outstanding difference between the lumped mass system branched off from the MDOF system which is generally applied as a means for the dynamic response analysis, and the EDEM system?" The difference lies between the respective system configurations, the former being characterized in that only continuous bodies can be analyzed while the latter, featuring its configuration, enables behavioral tracking over such a scope from a continuous body to a discontinuous body. Taking note of this system configuration, the EDEM system may be grasped as a means for the response analysis (extended MDOF) following the MDOF system characterized by an extended scope of application.

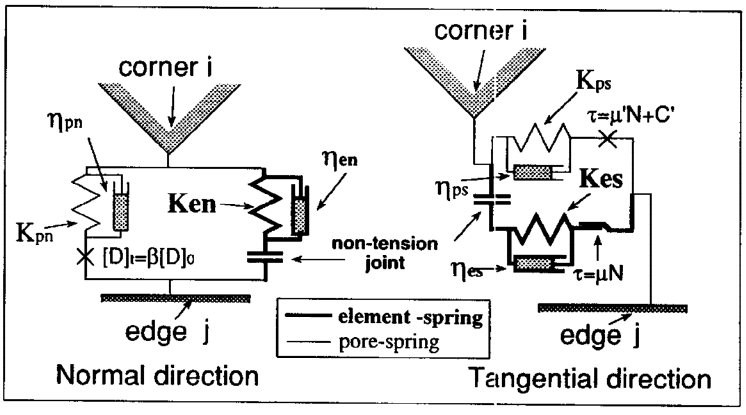


Fig. 1. EDE modelling

Depending upon the material characteristics of the medium concerned and the scales of the structures to be modeled by the EDEM, it is impractical and beyond the operational capability of present computers to have models in which the elements have one-to-one correspondence with those in the real medium. For example, in the case where basic vibration and subsequent collapse modes, both of which hold signifi-

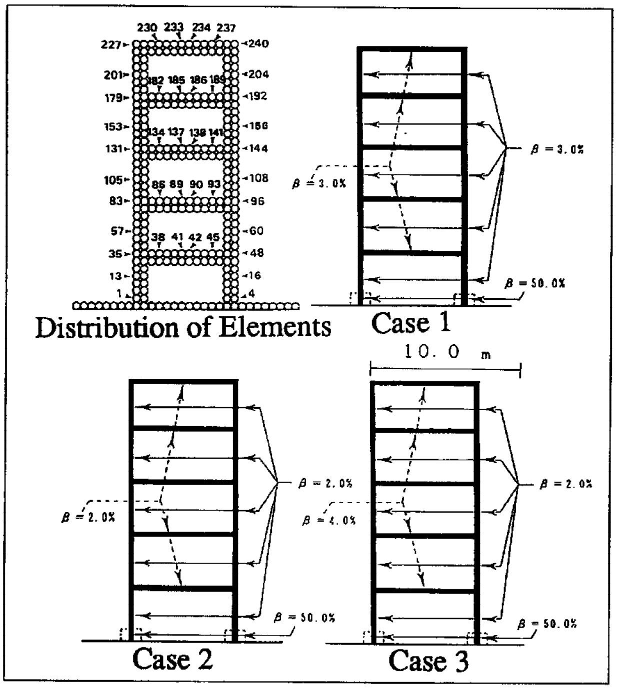


Fig. 2. Building models

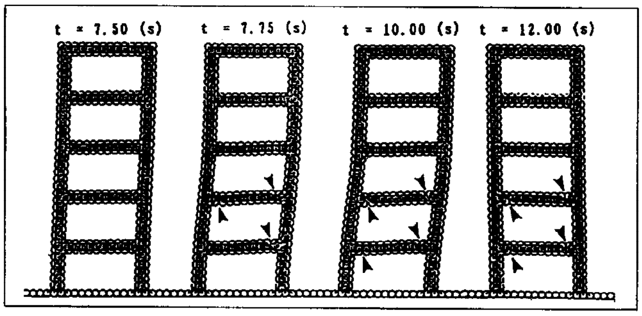


Fig. 3(a). Seismic response analysis of a slender building
(Casel: Example of earthquake damage to weak-beam-type buildings)

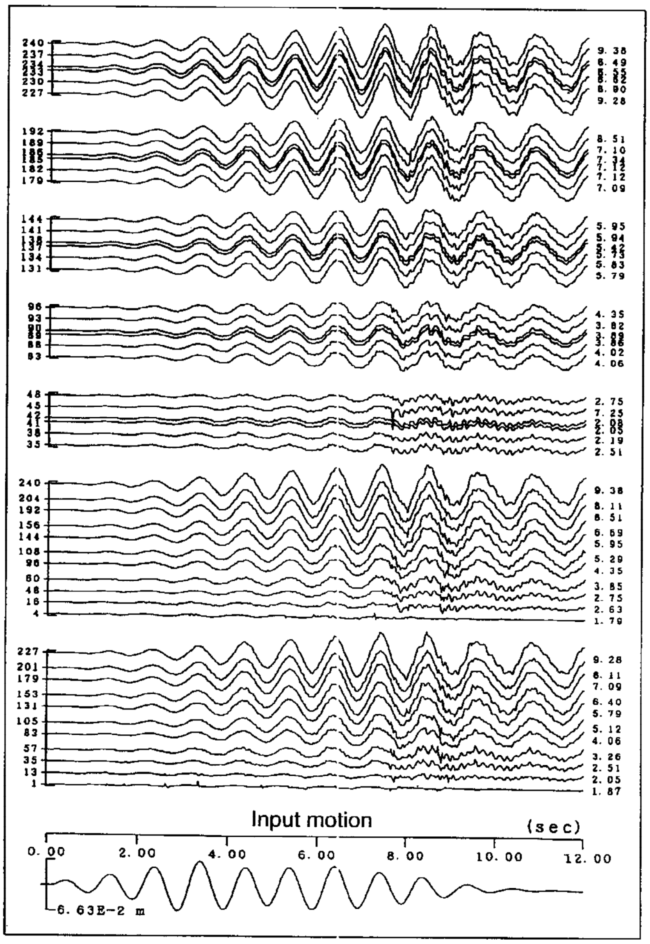


Fig. 3(b). Time-history of response velocity
(Horizontal comp. with Case 1)

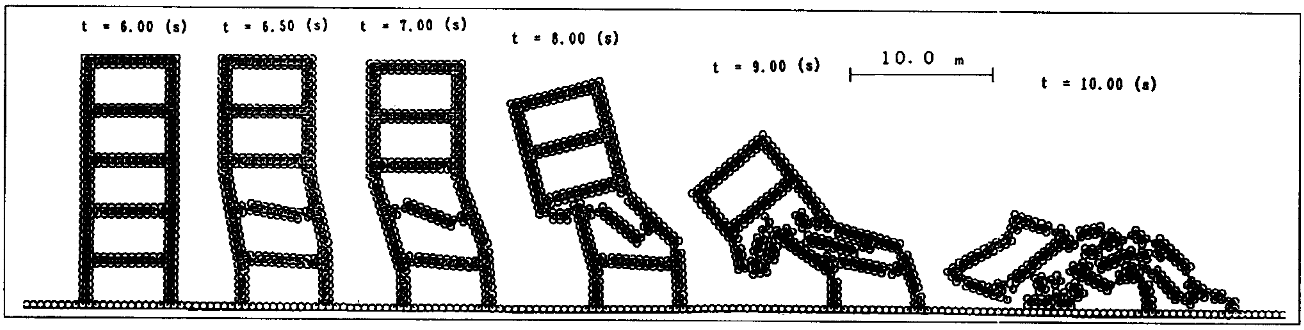


Fig. 4. Seismic response analysis of a slender building
(Case 2: Example of earthquake damage to weak-colomn-type buildings)

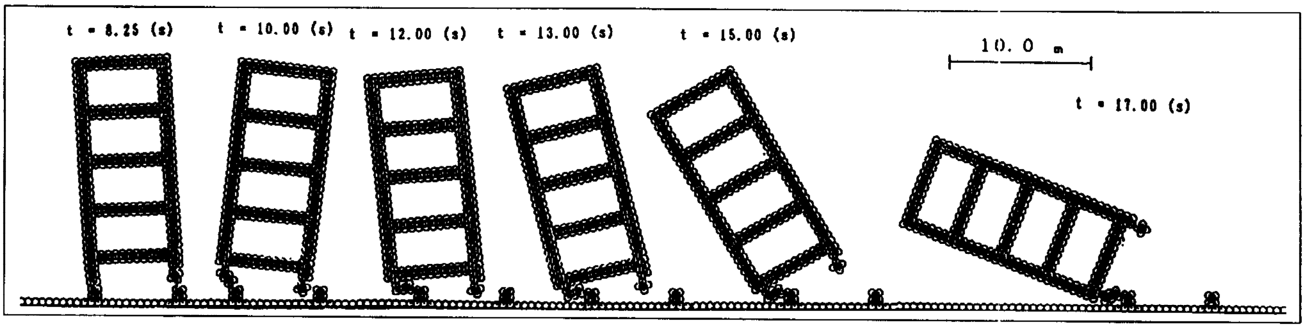


Fig. 5. Seismic response analysis of a slender building
(Case 3: Collapse of a slender building due to resonance)

cance in engineering, are required to be clarified, there is no need to model at the material level involving a large number of elements. In such a case, it is useful to consider the EDEM as an extended MDOF system, which can be applied to the collapse behavior of structure.

The dynamic response analysis by the conventional MDOF system is very difficult when analyzing the dynamic behavior in the stage of structural collapse initiation or in the process wherein structural collapse is progressing. However, the dynamic response analysis following the EDEM system allows us to simulate the collapse behavior of structures from a sound state to a complete collapse. Therefore, with the EDEM system dynamic response analysis, the structural vibration characteristics can vary with the outbreak of collapse, and keeping pace with the progress of collapse can phenomenally be illustrated in a state of spontaneity.

Examples of the EDE simulation are shown in **Figs. 2** to **5** (Meguro and Hakuno, 1989b). These are the analyses of dynamic behavior of the slender structures due to excitation. In case of the simulation using the model of case 1, cracks appear at the left and/or right beam-column connections of the 2nd and 3rd floors at 7.75 sec (**Fig. 3 (a)**). The effects of appearance and slips between the cracks can be seen in the velocity response at the joint corners. Because of the damage due to cracks, dynamic properties of the structure system is changed. Its natural period become longer as shown in **Fig. 3 (b)**.

NUMERICAL RESULTS

To study the mechanism of collapse of structures due to past earthquakes, Meguro and Hakuno simulated various modes of collapsed structures, some of which are shown in **Figs. 6** to **8** (Hakuno and Meguro, 1993). After the 1995 Great Hanshin earthquake, these types of structural collapse were observed in the affected areas (**Photos 1-3**).

In addition to the collapse of houses and building structures, elevated bridges of highways and railways were also severely damaged due to the 1995 Great Hanshin earthquake. Since the earthquake occurred early in the morning, fortunately, casualties due to the damage of civil infrastructures such as highways and railways were not so many. If the earthquake had hit during daytime when the people were outside and using infrastructures, many people may have been killed or severely injured due to the collapse of these structures. **Photos 4** and **5** show the collapse of elevated bridges of Hanshin Expressway. Considering the damage in **Photo 4**, although the piers didn't collapse but suffered some damage at the bottom, two adjacent simple-beam decks fell down due to dislocation of the bearing supports (**Fig. 9**). Seventeen piers spanning about 630 m of pilz-type bridges were destroyed and the bridges collapsed (**Photo 5**). To study the collapse mechanism of these elevated bridges, the fracture process of the damage was simulated using the EDEM.

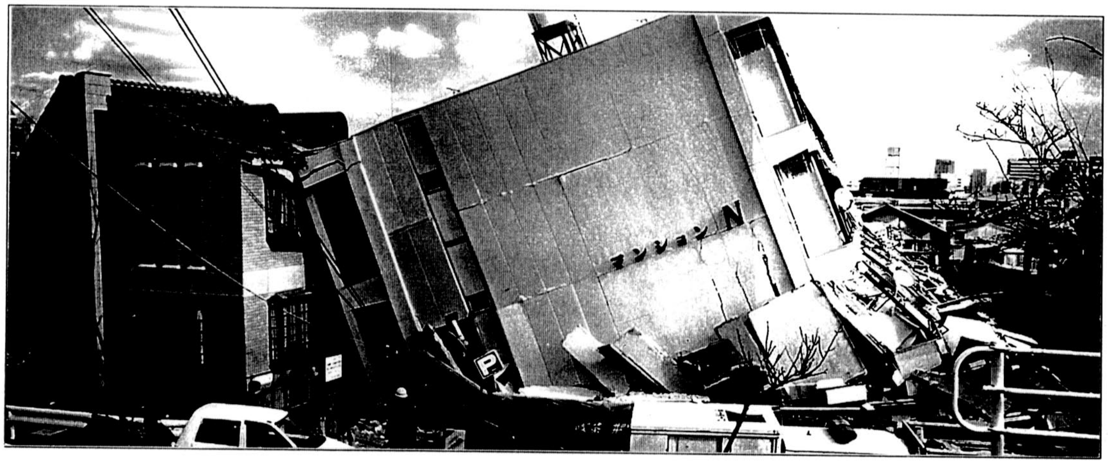


Photo 1 Tumbling-type collapse of buildings

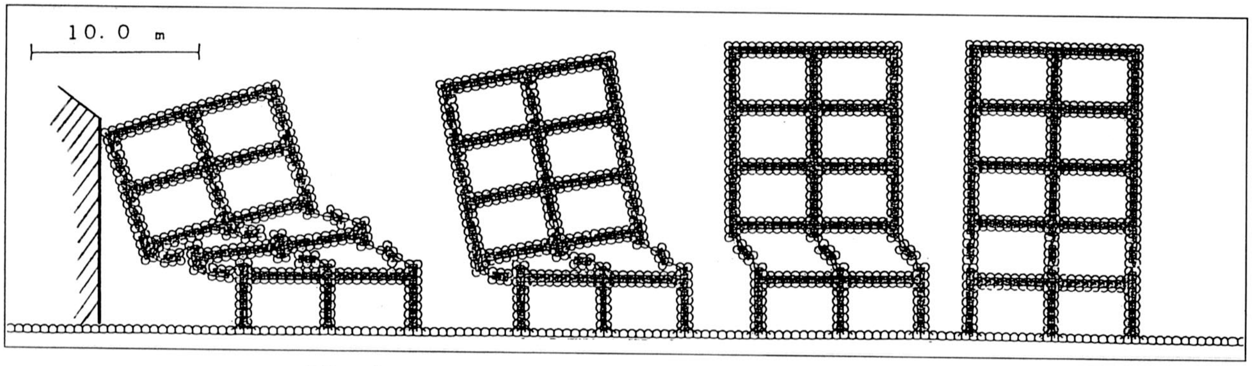


Fig. 6. EDE simulation of the tumbling-type collapse

Figures 10 and **11** show the damaged elevated bridge models for EDE simulation. Considering the fracture mode of the damage and computational time, we reduced the number of elements used and made the model simple. Since the ground motion at these sites were not recorded, numerical integrated displacement motion from the North-South (N-S) and East-West (E-W) components of the ground acceleration records at Kobe Marine Meteorological Observatory were used in the simulation (**Fig. 12**).

Using the model in **Fig. 10**, three cases of simulation with and without consideration of time lag due to wave propagation were simulated. Namely, one case without input time lag, and two cases with the lag based on the assumption that the wave in **Fig. 12 (b)** propagated from the left (east) to the right (west) with two different shear velocities (124 m/s and 296 m/s) estimated from the N values of the ground.

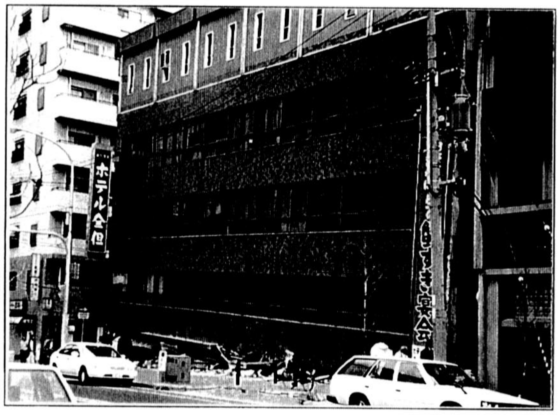


Photo 2 Damage to the first floor collapse-type

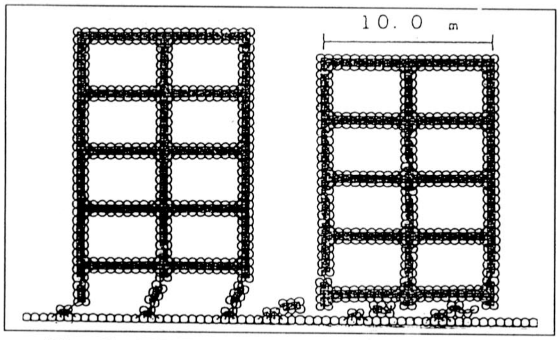


Fig. 7. EDE simulation of the damage to the first floor collapse-type

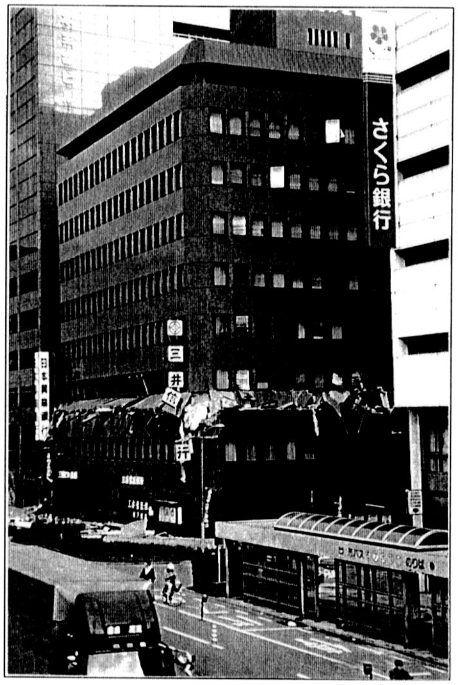


Photo 3 Damage to an intermediate floor collapse-type

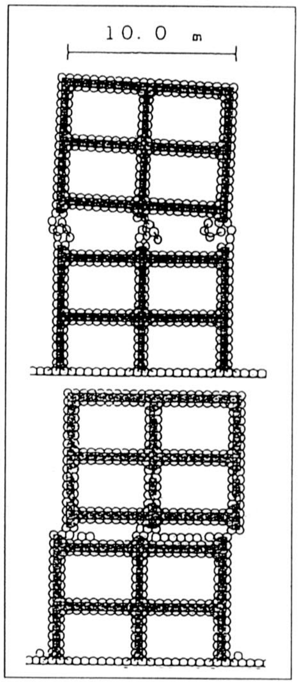
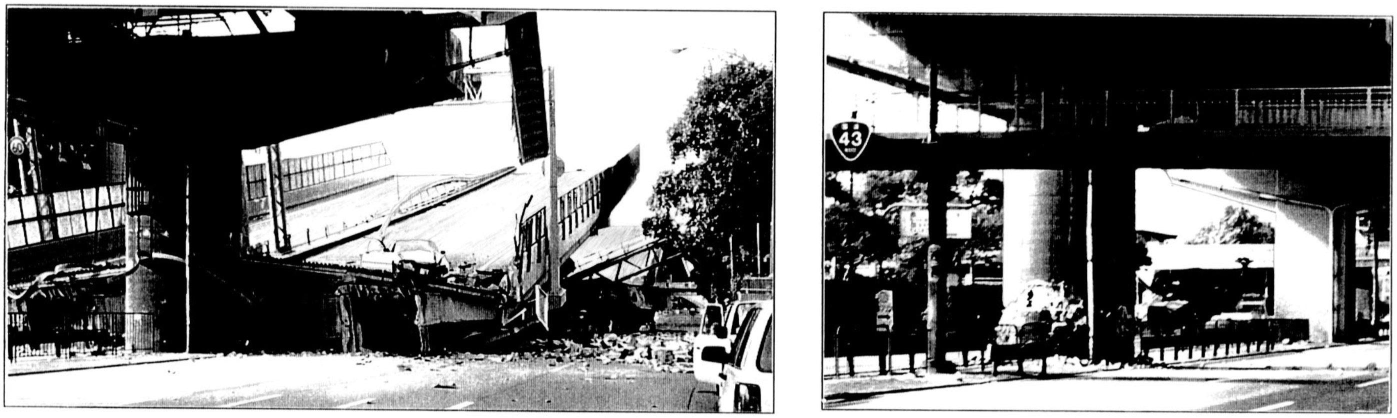


Fig. 8. EDE simulation of the damage to an intermediate floor collapse-type



(a) Fallen two adjacent simple-beam decks

(b) Damaged bottom of the pier, P1

Photo 4 (a) Damage to elevated expressway bridge

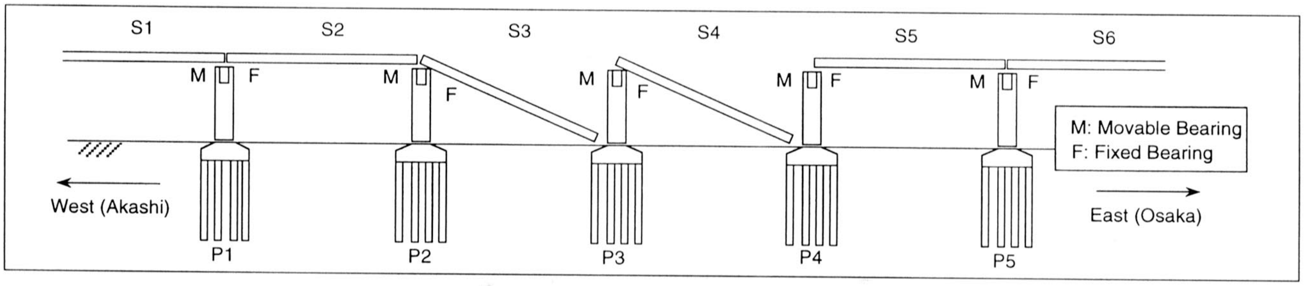
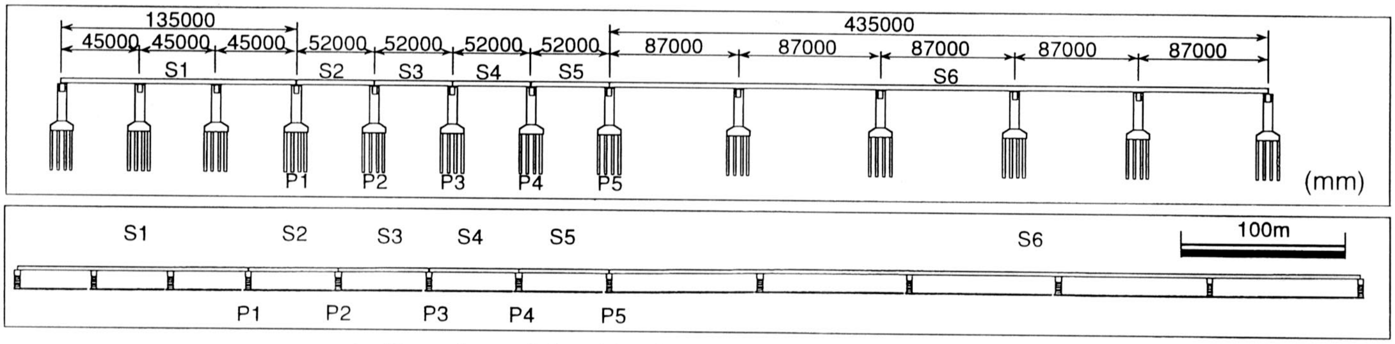


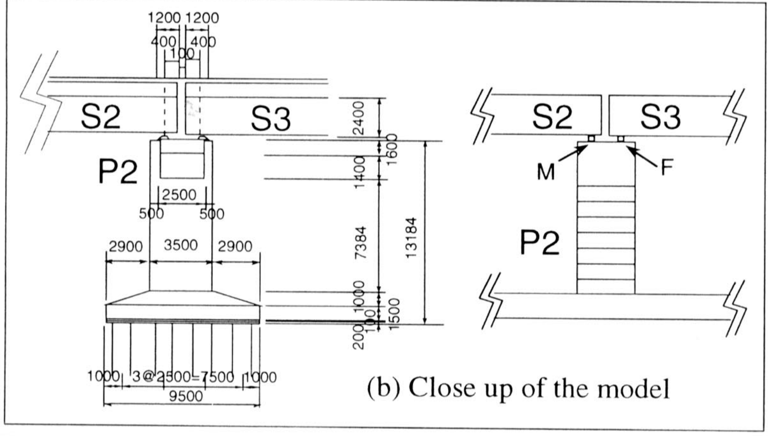
Fig. 9. Collapse mode of elevated bridge in **Photo 4**

In the case without input time lag there was no collision between decks while in other two cases, decks hit each other. **Figure 13** shows the displacement responses of each girder in case of Vs=124 m/s. Collision between decks can be seen in the response and its effects on the deck is shown at the response acceleration of the deck (**Fig. 14**). **Figures. 15** and **16** are the time-history of the forces acting on fixed bearing between P1 and S2 and the bottom of pier P1, respectively. In the cases with input time lag, impact loads acting on the piers and shoes are seen and they might cause the destruction of shoes and bottom of the piers (**Photo 4(b)**). These results in **Figs. 13** to **15** are linear response analyses in which pore-springs set between elements are not destroyed. **Figure 17** shows the fracture process in case of Vs=124 m/s. Two simply supported decks of the elevated bridge fell down. The collapse mode obtained here is very similar to that of actual damage as shown in **Photo 4**. The difference between actual case and simulation is that S3 and S4 decks fell down in real damage, while S2 and S3 did in the simulation. Considering the uncertainties of input ground motions and some boundary conditions, this simulation result explains the mechanism of the damage as shown in **Photo 4**.

With the model in **Fig. 11**, collapse process of the damage to elevated expressway bridges due to overturning was simulated. This was the symbolic damage during the Great Hanshin earthquake shown in **Photo 5**. As an input motion, the ground motion in **Fig. 12(a)** was adopted. Simulation of collapse process is shown in **Fig. 18**. With time, the bridge inclined and finally, overturned. Although the exact collapse process is not reported, the final collapse mode obtained in this study agrees with that of the real damage.



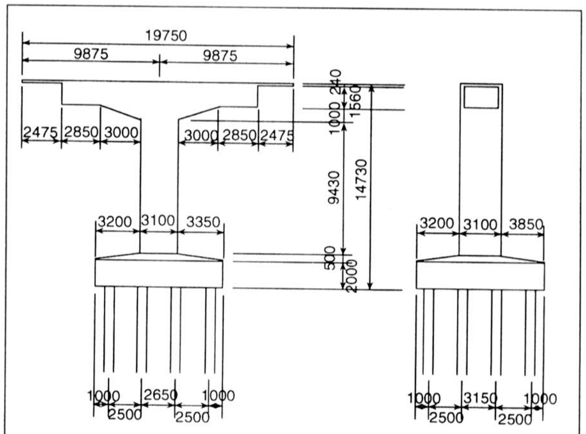
(a) Overview of the objective bridges and simulation model



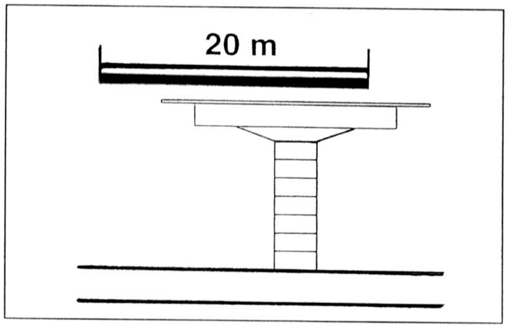
(b) Close up of the model

Fig. 10. Size of the bridges and simulation model (Model A)

Photo 5 Collapse of pilz-type bridges

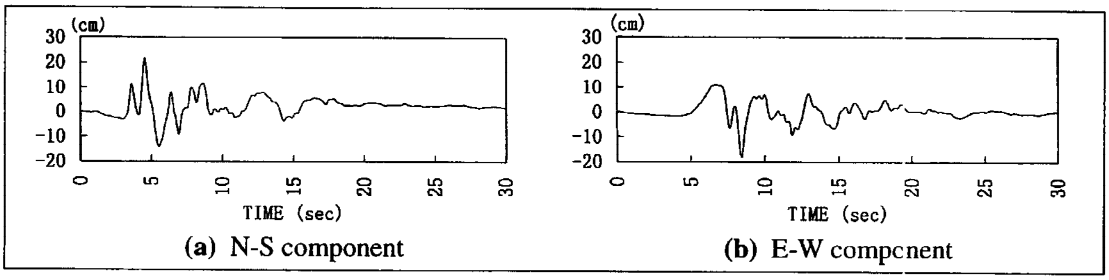


(a) Size of the pilz-type bridges



(b) Simulation model

Fig. 11. Size of the pilz-type bridges and simulation model (Model B)



(a) N-S component

(b) E-W compcnent

Fig. 12. Input groung motion

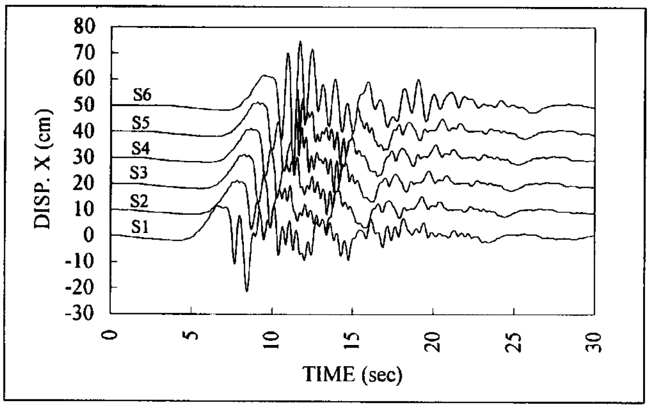


Fig. 13. Horizontal response displacement of decks

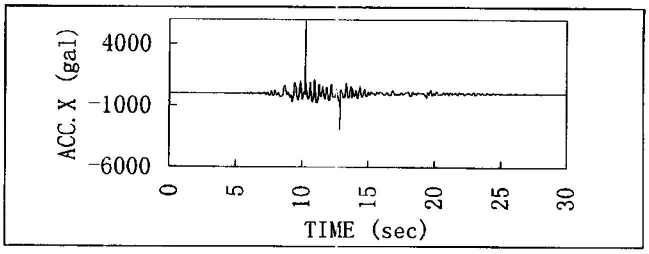


Fig. 14. Horizontal response acceleration of the deck, S2 (with input time lag, Vs=124 m/s)

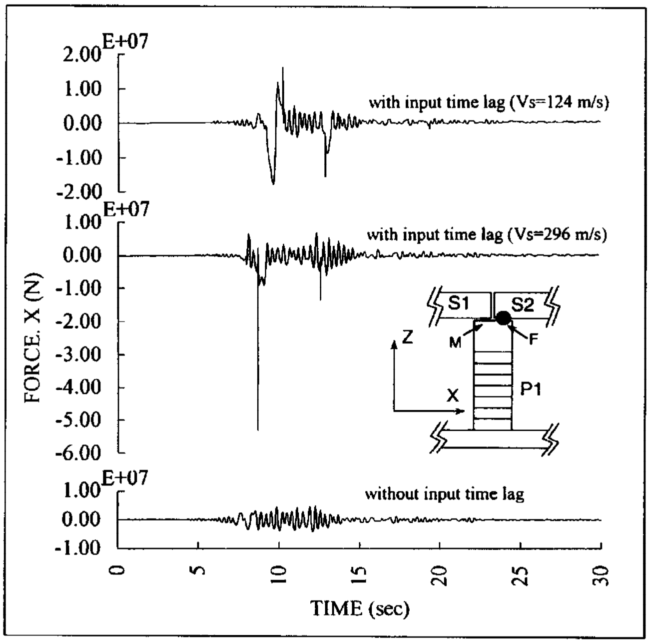


Fig. 15. Forces acting on the fixed bearing between P1 and S2

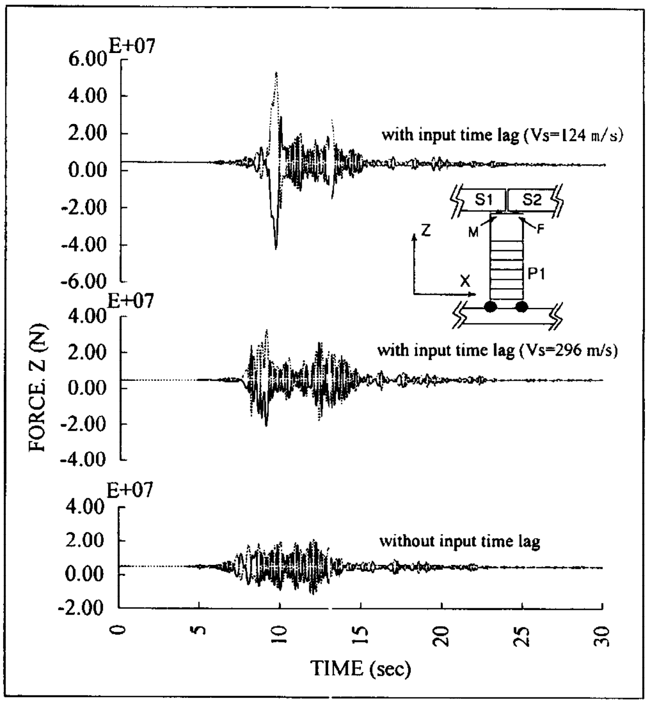
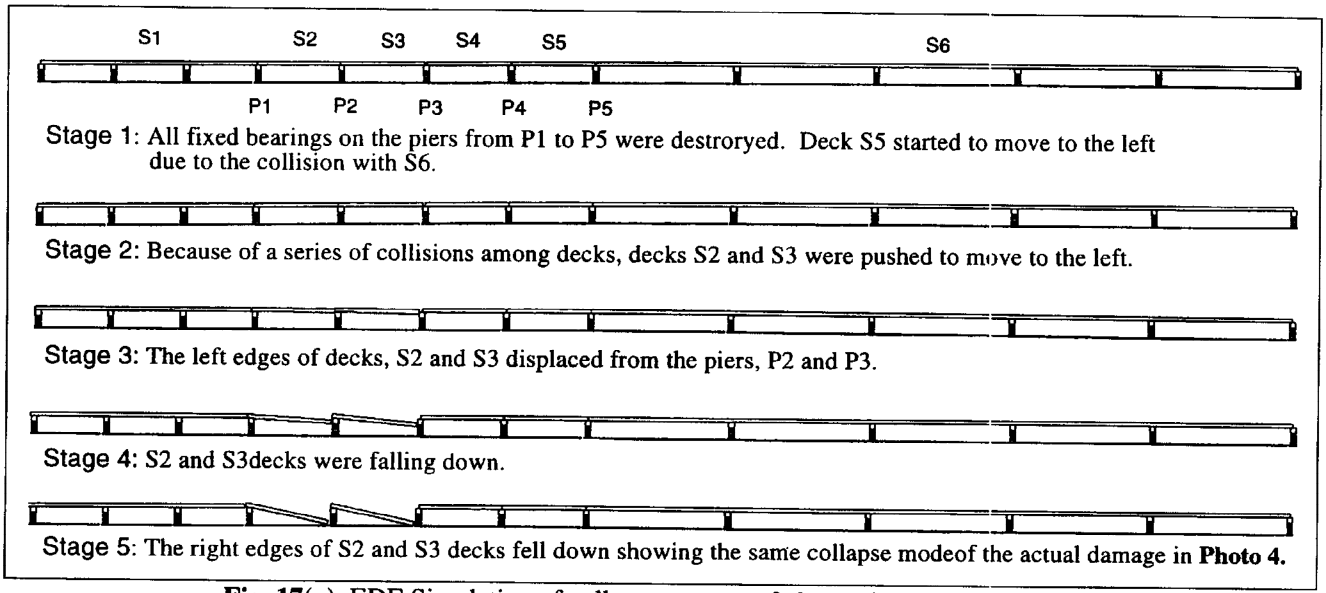


Fig. 16. Forces acting on the bottom of the pier, P1

CONCLUSION

Using the EDEM, we tried to simulate the collapse process of structures due to the 1995 Great Hanshin earthquake in order to study the mechanism of the damage. These simulations are based on the new concept of the EDEM application in which the EDEM is taken as an enhanced lumped mass system. Although the phenomena treated in this study were difficult to be simulated by the conventional methods such as the finite element method, the numerical results obtained by the EDEM agree well with the real earthquake damage.

Examining the simulation results, a conclusion can be drawn that the macro models of these structures would be capable of demonstrating to some extent as to how structures would undergo local collapse, whereby the models be allowed to account for the process or the mechanism of actual earthquake-caused structural collapse with certain accuracy. Although the EDEM is required to go through improvements over various points, the results for fracture as a whole, generally replicate observed earthquake damage.



Stage 1: All fixed bearings on the piers from P1 to P5 were destroryed. Deck S5 started to move to the left due to the collision with S6.

Stage 2: Because of a series of collisions among decks, decks S2 and S3 were pushed to move to the left.

Stage 3: The left edges of decks, S2 and S3 displaced from the piers, P2 and P3.

Stage 4: S2 and S3decks were falling down.

Stage 5: The right edges of S2 and S3 decks fell down showing the same collapse modeof the actual damage in **Photo 4.**

Fig. 17(a). EDE Simulation of collapse process of elevated expressway bridges

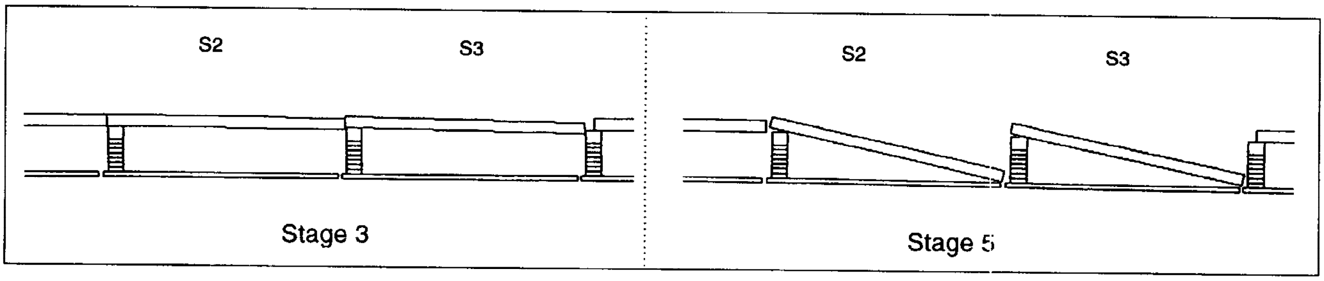


Fig. 17(b). Close up of collapsed parts

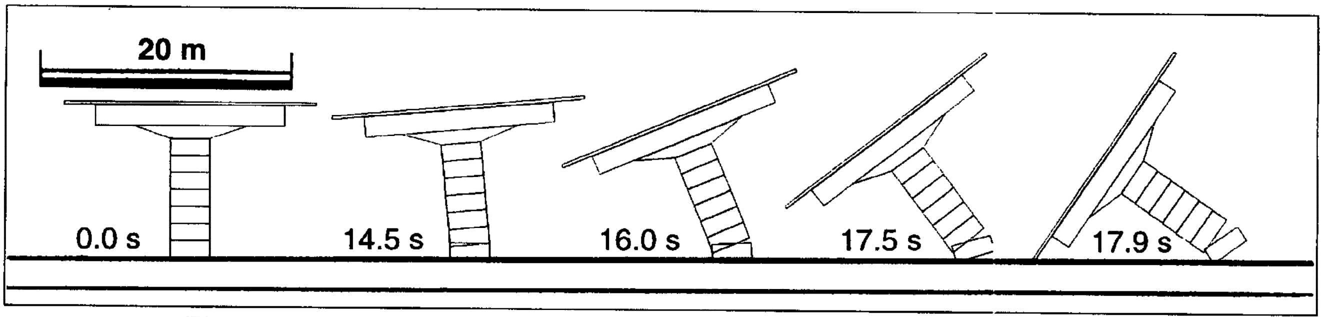


Fig. 18. EDE simulation of collapse process of pilz-type elevated expressway bridges

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