Development of Seismic Damage Finite Element Code for Reinforced Concrete Framed Structures

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Summary

A new finite element code using the Adaptively Shifted Integration (ASI) technique with a linear Timoshenko beam element, which can express member fracture by a plastic hinge located at an exact position with a simultaneous release of the resultant forces in the element, is applied to the seismic damage analysis of reinforced concrete (RC) framed structures. Contact between members is also considered in order to obtain results that agree more closely with actual behaviors such as intermediate-layer failure. By using the proposed code, sufficiently reliable solutions have been obtained and the results reveal that this technique can be used in the numerical estimation of structural reliabilities.

Introduction

In the conventional design of a building, only static analysis in the horizontal and uniaxial directions is commonly carried out, in order to minimize calculation costs. This approach may ensure the structural strength of the building, if there is sufficient strength to support the load in vertical direction. However, the mass system model replaces the building layer in dynamic analysis, and the complicated dynamic behavior of the structure at member level is not sufficiently examined. Therefore, the development of a more precise and more efficient dynamic analysis code is strongly desired. Recently, significant advances in the field of computers have been removing the calculation cost restrictions, and various dynamic analysis codes are being developed. In this study, the Adaptively Shifted Integration (ASI) technique [1] is implemented into the finite element code in order to develop a more precise and less calculation- time-consuming seismic response analytical tool.

The purpose of this study is to verify the validity of the ASI technique in seismic response analysis and to construct a highly efficient structural design tool for RC structures. Analyses considering vertical seismic excitation or the phase difference of seismic-wave propagation, and those involving structural discontinuities such as member fracture are carried out as numerical examples. A contact algorithm is added to the code to reproduce phenomena such as intermediate-layer failure.

Adaptively Shifted Integration technique

In the ASI technique, the numerical integration points in an elastically deformed beam element are placed at the optimal points for linear analysis (midpoint in the linear Timoshenko beam), and are immediately shifted after the occurrence of a fully plastic section in the element, using previously established relation between the location of a numerical integration point and that of a plastic hinge [1], to form a plastic hinge exactly at the position of the fully plastic section. In this manner this technique produces a higher computational accuracy with fewer elements than the conventional finite element code. Member fracture can also be considered by shifting the numerical integration point with a simultaneous release of resultant forces in the element. In addition, the implementation of the technique in the finite element code is reasonably easy. Numerical tests concerning the geometrically nonlinear,

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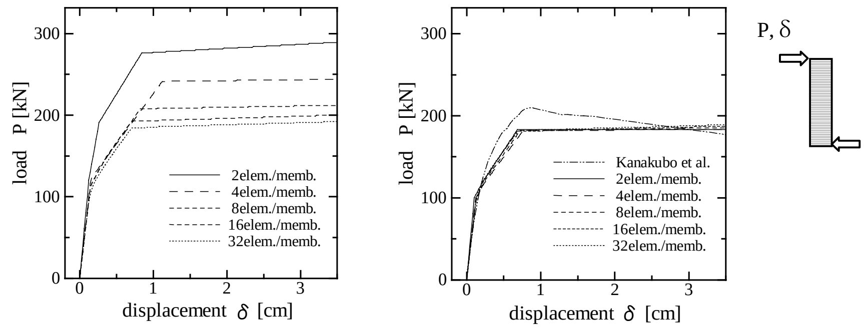


(a)Conventional code **(b) ASI technique**

Fig.1 Simply supported column subjected to shear force

elasto-plastic analysis as well as the geometrically linear, plastic collapse analysis and the dynamic collapse analysis, are shown in papers [1~3].

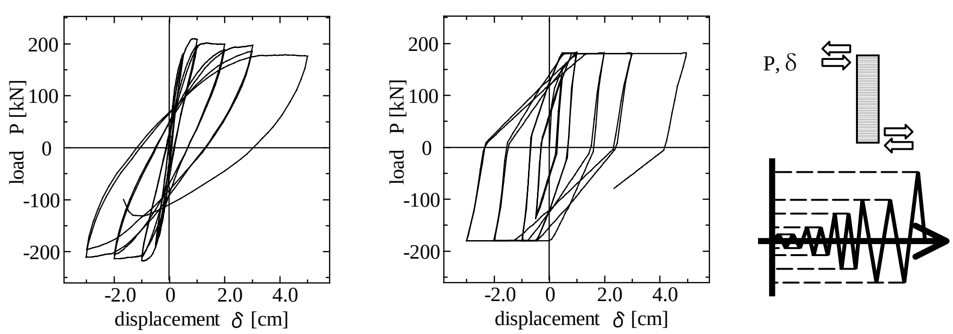
Static and quasi-static analyses of RC structures

First, the validity of the ASI technique in the static and quasi-static analyses is verified. In the static and quasi-static analyses for a frame member, it is demonstrated that the converged solution can be obtained by only two-element subdivision per member in the ASI technique, while more elements are required in order to obtain the converged solution in the conventional finite element code (Fig.1). Furthermore, it is verified by comparison with the experimental value [4] that the degrading tri-linear model, which is applied for RC modeling, is appropriate (Fig.2).

As a result of static analysis on a twelve-story, three-span existing structure, it is revealed that the modeling and analysis by the ASI technique are appropriate based on the consideration of output such as the plastic chart (Fig.3) and the drift angle distribution (Fig.4). The computing time using SUN ultra 5 (CPU: 270MHz, memory: 128MB) is approximately 10 minutes.

Seismic response analysis of RC structures

Second, a seismic response analysis is carried out to verify the validity of the proposed code. Seismic excitation is applied to the fixed nodal points. Although comparison with the experimental



(a) Experiment [4] **(b) ASI technique (2elem./memb.)**

Fig.2 RC column under repeated quasi-static load

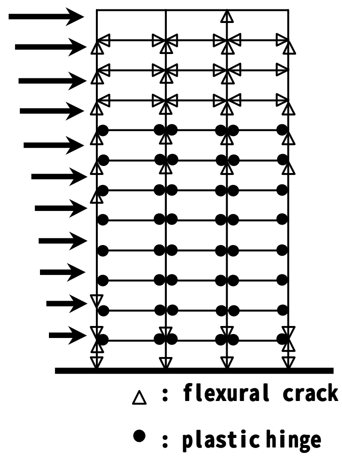


Fig.3 Plastic chart

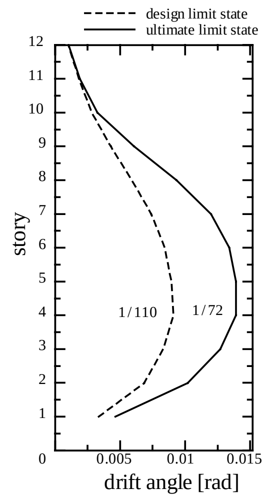
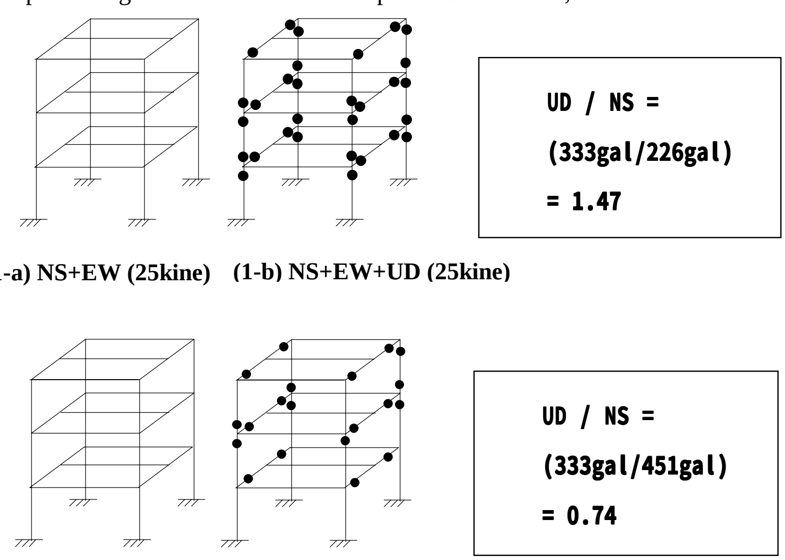


Fig.4 Drift angle distribution

value reveals that attention is needed for handling the stiffness, inertial mass and damping caused by the existence of floors and walls, etc., a practically useful solution can be obtained by using the proposed code.

It has been mentioned that very large vertical ground excitation was one of the factors in which the damage expanded in the Great Hanshin-Awaji Earthquake. By carrying out an analysis under a three-directional seismic wave, an increase in the number of plastic hinges as well as the differences of deformed configurations is observed. As shown in Fig.5, this phenomenon depends upon the ratio of the vertical amplitude against the horizontal amplitude. Therefore, the results obtained by dynamic



(1-a) NS+EW (25kine) **(1-b) NS+EW+UD (25kine)**

(2-a) NS+EW (50kine) **(2-b) NS+EW+UD (50kine)**

Fig.5 Plastic chart obtained from three-directional excitation analysis (JMA Kobe)

analysis only under horizontal loads may be overestimated to the safe side, and further investigation is required.

Seismic response analysis considering the phase difference of seismic-wave propagation

As an application of the proposed code, the effect of the phase difference of seismic-wave propagation on a structure is estimated. A horizontal seismic wave is assumed to spread from a hypocenter at a constant rate in a concentric circular plane in this study. An input seismic wave is made to produce a time difference by calculating the time difference in the arrival of the seismic wave by dividing the distance between each fixed nodal point by the horizontal seismic-wave speed. Interactions between the ground and the structure, the attenuation of the seismic wave and so forth, are not considered. Figure 6 shows the plastic charts of an eight-story, three-span building subjected to seismic excitation with no phase difference, in the cases of wave propagation speeds of 10km/sec and of 5km/sec. The burden of the beam increased with the change in the differential arrival time of the input seismic wave, and the influence against the generated number of plastic hinges is confirmed. Therefore, the results obtained in the analyses not considering phase difference must be handled carefully in the design stage, since there is a possibility of overestimating to the safe side.

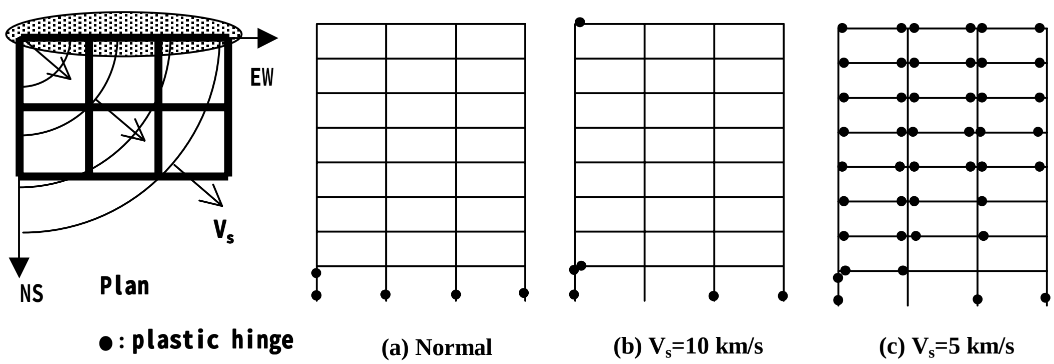


Fig.6 Seismic response analysis considering the phase difference of wave propagation

Seismic damage analysis considering member fracture and contact

Phenomena with strong nonlinearity and discontinuities such as member fracture are easily analyzable using the proposed code. However, behavior such as the penetration of a member through a floor could be observed in the analyses [3], since contact between members was not considered. Actually, some structures observed in the Great Hanshin-Awaji Earthquake were collapsed in the intermediate layer and as a result, the upper layer piled up on the layer. Although there are some numerical examples using the Distinct Element Method (DEM) that consider contact between members, there are no application examples using the FEM that can continuously analyze the behavior from the elastic stage to the collapse stage. Thus, a contact algorithm is added to the proposed code and applied to the seismic damage analysis to reproduce the intermediate-layer failure phenomena.

Member fracture is determined by examining the ductility factor and the shear strain in all elements, and is expressed by shifting the numerical integration point of the fractured element with a simultaneous release of the resultant forces in the element, as shown in Fig.7. The distance between the fractured element and the other element is calculated, and the contact is determined from the distance between each node and by the condition under which all four nodal points exist on an identical plane.

Once two elements are judged to be in contact, a total of four gap elements are fixed between the nodal points, as shown in Fig.8.

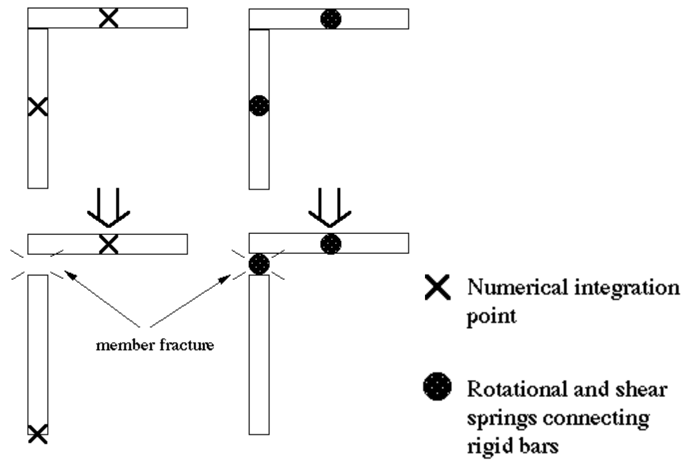


Fig.7 ASI technique dealing with member fracture

Figure 9(a) shows a case in which only member fracture is considered, and Fig.9(b) shows the result when the contact algorithm is added to the code. The total number of elements is 464, and that of nodal points is 340. The computing time using SUN ultra 5 (CPU: 270MHz, memory: 128MB) is approximately 50 minutes. By considering the contact between members, the reproduction of seismic damage observed in actual earthquakes such as intermediate-layer failure became possible.

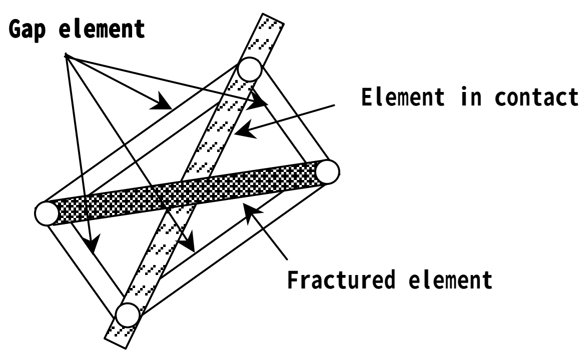
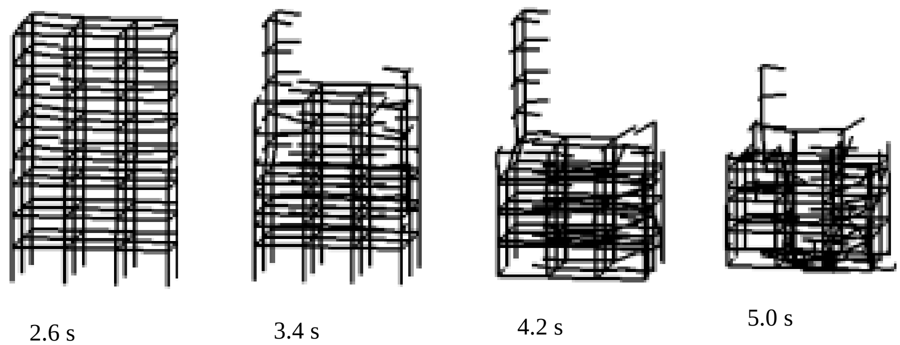


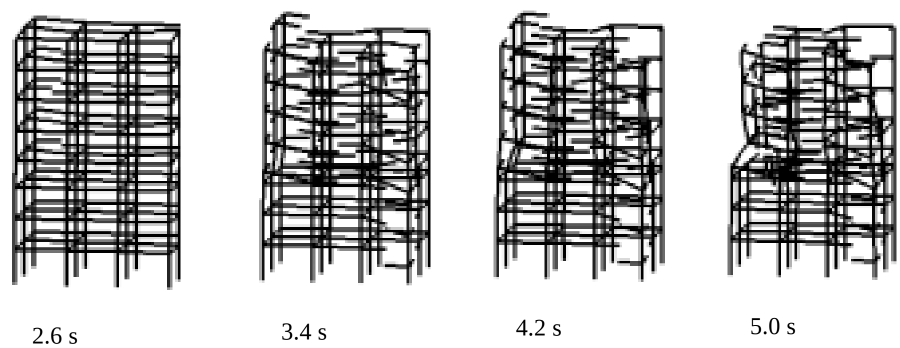
Fig.8 Binding condition of gap element

Concluding remarks

In this paper, a nonlinear finite element code using the ASI technique is used to verify the validity in static and dynamic response analyses, and it is applied to seismic damage analyses including structural discontinuities. The fracture of a section is modeled by shifting the numerical integration



(a) Without using contact algorithm



(b) Using contact algorithm

Fig.9 Seismic damage analysis of RC framed structure

point with a simultaneous release of the resultant forces. The proposed code is improved by considering the contact between members in order to obtain results that agree more closely with actual behavior. The results reveal that this technique can be used in the numerical estimation of structural reliabilities.

Reference

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