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Development of integrated system for progressive collapse analysis of building structures considering dynamic effects

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ABSTRACT

In this study the integrated system for progressive collapse analysis, which can evaluate the damage level of every member and automatically construct the modified structural model for the next analysis step, has been developed. The existing nonlinear analysis program code OpenSees was used as a finite element solver in the integrated system for progressive collapse analysis. The developed integrated system includes a pre-processor with intuitive graphic user interfaces and a post-processor that can simulate the progressive collapse by 3D graphic animation. Using the developed integrated system, example structures subjected to a column failure were analyzed, and the behavior of the structures was investigated in the context of how to model the failed members and whether the dynamic effects are considered or not. The analysis results show that the dynamic amplification can be larger than two which is recommended by the GSA and DoD guidelines and the collapse mechanism depends greatly on the modeling technique for failed members.

1. Introduction

Progressive collapse occurs when local failure of a primary structural component leads to the failure of adjoining members and finally to the failure of partial or whole structure system. It is a dynamic process, usually accompanied by large deformations, in which the collapsing system continually seeks alternative load paths in order to survive. One of the important characteristics of progressive collapse is that the final damage is not proportional to the initial damage.

In 1968 a gas explosion occurred near the top of the Ronan Point apartment building in London, and the failure of supporting members was vertically propagated and resulted in progressive collapse [1]. Since that time researches on this issue were performed intermittently until the terrorist attacks against the Alfred P. Murrah Building in Oklahoma City in 1995 and the World Trade Center in New York in 2001 accelerated research in this field [2–4].

To prevent or reduce the risk of progressive building collapse, many building codes integrated an indirect design approach into the specifications through mandatory strength, ductility and continuity requirements [5–7]. Recently, both the US General Services Administration (GSA) [8] and the US Department of Defense (DoD) [9] have issued guidelines for evaluating the progressive collapse hazard which provides general information about the approach and method of evaluating the progressive collapse potential. In these guidelines, a direct design procedure known as 'Alternate Load Path Method' was recommended as a simplified analysis technique for investigating the potential of progressive collapse in the design of buildings. In this analysis, information on static load redistribution for the structure under consideration is obtained but the inevitable dynamic effects are not taken into account. Instead a dynamic amplification factor of 2 is used to account for dynamic effects indirectly in the GSA and the DoD guidelines. However Pretlove et al. [10] demonstrated that a static analysis for progressive failure may not be conservative if inertial effects are taken into consideration. Although several researchers presented the importance of considering inertial effects for progressive collapse analysis, dynamic load redistribution in the progressive collapse analysis of frame structures is hardly considered in practicing engineering because most of commercial softwares do not support progressive collapse analysis with dynamic effects.

In the GSA and the DoD guidelines, there are three allowable analysis procedures for progressive collapse analysis: i.e. linear static, nonlinear static, and nonlinear dynamic procedures. An advanced structural analysis computer program such as SAP2000 is generally required to perform a sophisticated progressive collapse analysis. However, a commercial structural analysis program usually does not provide user interfaces or modules specially designed for progressive collapse analysis. Thus, complicated and repetitive procedures are required for practicing engineers to perform progressive collapse analysis of buildings by using a general-purpose

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structural analysis program. That is, after initial failure of a column member, structural analysis is performed by one of three analysis procedures to evaluate whether progressive collapse occurs or not. To this end, structural responses and damage levels of all the members should be investigated by comparing with failure criteria. If another members turn out to fail, re-analysis with the modified analytical model representing the next structural configuration should be performed. By applying this procedure, repetitive analyses are required until no progressive failure occurs in structural members. Especially, in the case of high-rise and large-scale buildings in which significant damage is expected, evaluation of failure criteria for every structural member and construction of a new analytical model for re-analysis will take a lot of time and efforts. In addition it is quite possible that operational errors occur during the iterative process.

Several researches on the development of analytical tools for progressive collapse analysis were conducted [11,12]. Complicated source level development of the finite element solver to simulate dynamic progressive collapse problems that contain strong nonlinearities and discontinuities would take significant time and efforts. Moreover, it is not easy to verify the accuracy and robustness of the developed solver. In this regard Choi and Krauthammer [12] used a commercial analysis program, ANSYS, as a solver for progressive collapse analysis by introducing an external criteria screening technique.

In this study the nonlinear analysis program code OpenSees [13] developed by the Pacific Earthquake Engineering Research (PEER) Center in UC Berkeley was used as a finite element solver for progressive collapse analysis to develop the integrated progressive collapse analysis system which includes modeling, analysis, evaluation of damages, graphic simulation, etc. Using the integrated system, various progressive collapse scenarios can be easily simulated. The integrated system calculates damage index of every structural member based on the user-defined failure criteria and automatically construct the modified structural model for each progressive collapse analysis step.

As the OpenSees is a non-commercial software for numerical analysis, sate-of-the-art technologies can be directly adopted in the integrated system. Progressive collapse analyses of example frame structures were performed by using the integrated system developed in this study. Based on the numerical simulation, the importance of dynamic effects in progressive collapse analysis was evaluated and the effect of the different modeling method of the failed members was investigated. The integrated system was developed by the Visual C++ and the MFC (Microsoft Foundation Class), and the OOP (Object-Oriented Programming) was employed for easy modification and upgrade of the system. To easily understand the progressive collapse mechanism, a post-processor having a graphic animation module has been developed by using the 3D graphic library, OpenGL.

In this study the failure of structural members was determined by the flexural capacity of members as recommended in the GSA and the DoD guidelines. However, it is not uncommon for steel structures to fail due to premature failure of connections. This, however, is difficult to predict in numerical analysis, and therefore it was assumed in the structural analysis that all connections have their full design capacity and failure occurred only in structural members.

2. Primary elements for progressive collapse analysis

2.1. Damage index

When progressive collapse occurs following an initial member failure, other structural members undergo various levels of damage and some of them may reach to the state of failure. In order to define failure of a damaged member, a damage index needs to be defined as a damage indicator. In the literature, several damage indices have been proposed for concrete members [14,15] and for steel members [16,17]. Colombo and Negro [18] proposed a generalized damage index that can be used independently of the structural material. In this study, the generalized damage index shown in Eq. (1) based on strength deterioration was employed to indicate damage level of structural members:

$$D = 1 - \frac{M_{ac}}{M_{y0}} \tag{1}$$

$$M_{ac} = M_{y0} \cdot f\left(\mu, \int \mathrm{d}E\right) \tag{2}$$

where M_{ac} is the deteriorated value of the yield moment and M_{y0} is the theoretical yield moment of undamaged members. As shown in Eq. (2), the deteriorated value of the yield moment is calculated by the theoretical yield moment multiplied by the evolution equation $(f(\mu, \int \mathrm{d}E))$, and it is a function of the maximum attained deformation (μ) and the dissipated energy ($\int \mathrm{d}E$). Colombo and Negro [18] divided the evolution equation into two parts, i.e. the ductility-based function and the energy-based function. The energy-based function has two different terms for separate modeling of the phenomena affecting the ductile and the brittle behavior of structural members to effectively present damage models of various materials. Since the damage index is employed for damage assessment of frame structures in progressive collapse analysis, dynamic effects due to sudden failure of structural members and unusually large deformation will mainly affect damage levels of structures rather than the accumulated damage from cyclic inelastic deformation. Therefore only the ductility-based function was adopted in this study for damage assessment as shown in Eq. (3):

$$f(\beta_1, \mu) = \left(1 - \frac{\mu_{\max}}{\mu_{\mathrm{u}}}\right)^{1/\beta_1} \tag{3}$$

where μ_{u} and $\mu_{\max}$ represent the ultimate and the maximum attained ductility, respectively, and β_1 is the accelerator factor. The parameter β_1 modifies the slope of the hardening/softening branch of the stress–strain curve to represent various characteristics of structural materials. The damage index (D) shown in Eq. (1) has a value ranging from 0 (no damage) to 1.0 (total damage). In this study, the integrated system evaluates the damage indices of all the structural members based on the analytical results at every analysis step. When the damage index of a structural member becomes 1.0, it is considered as failed.

2.2. Nonlinear material model

Since progressive collapse is inherently a nonlinear event, nonlinear analysis rather than linear-elastic analysis is desirable to investigate the progressive collapse potential and the collapse mechanism of buildings. Accordingly, in this study nonlinear static and dynamic analyses were performed for progressive collapse analysis. Fig. 1 shows the nonlinear hinge model generally used for nonlinear analysis of structures. The model, which is expressed by the yield moment (M_{y}), the maximum moment (M_{u}), the yield curvature (ϕ_{y}), and the maximum curvature (ϕ_{u}), was used in the DoD guideline for nonlinear analysis of a 5-story example structure using the program code SAP 2000 [19].

Once structural elements are damaged, degradation of element stiffness as well as strength occurs. As the level of damage increases the deformation of members and the system damping also increases, which affects the overall behavior and collapse mechanism of the structure. Therefore the phenomenon of stiffness and strength degradation needs to be included in the analytical

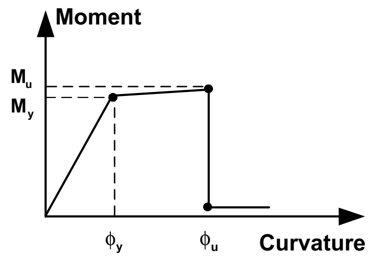


Fig. 1. Nonlinear hinge model.

modeling of the structure for accurate simulation of progressive collapse. The OpenSees provides various nonlinear material models, in addition to the nonlinear hinge model shown in Fig. 1, such as 'Hysteretic Material with Damage' and 'PINCHING4'. Especially the PINCHING4 material model allows three different representations of stiffness and strength degradation phenomena depending on damage level, such as unloading stiffness degradation, reloading stiffness degradation, and strength degradation as shown in Fig. 2.

2.3. Analytical modeling for failed members

As mentioned previously a structural member is considered as failed when its damage index reaches a unit value. Once failure occurs in one of structural members the mass matrix, stiffness matrix, and load vector are changed instantly. In this study it was assumed that plastic hinges form only at the ends of structural elements. If the nonlinear hinge model shown in Fig. 1 is used for the progressive collapse analysis, the ends of beam members will be modeled as hinges once the damage indices become 1.0 as shown in Fig. 3a. In this case the programming of analysis procedure is quite simple since the member ends will automatically becomes hinges and reformulating mass and stiffness matrices is not necessary. In this way the moment-resisting capacity of the failed members can be eliminated; however the axial or shear force-resisting capacities still remain and the behavior of the failed member cannot be modeled accurately. Therefore in this study new node is generated at the end of the failed members to separate the member end from the node as shown in Fig. 3b. The integrated system developed in this study automatically generates the input file for the OpenSees by inserting new nodes for failed members. In this paper the two different modeling techniques shown in Fig. 3a

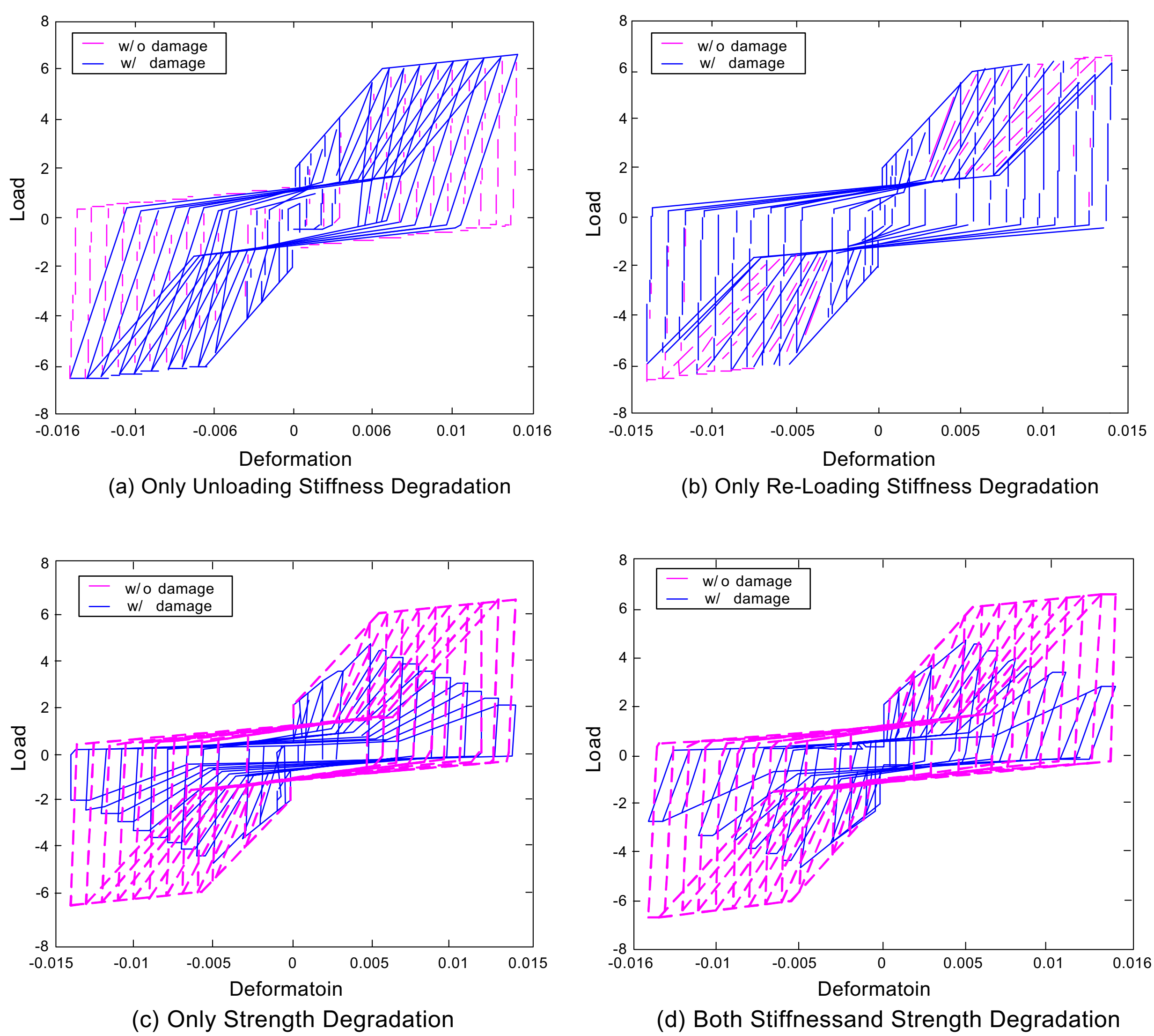


Fig. 2. Hysteresis loops with stiffness and strength degradation obtained by PINCHING4 model [18].

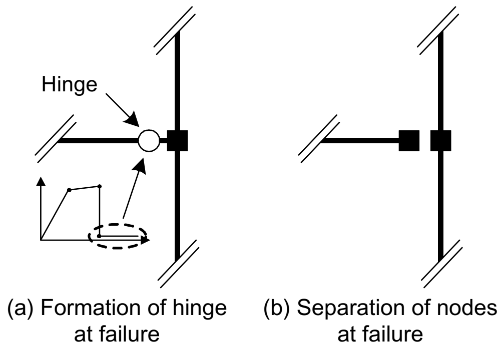


Fig. 3. Modeling of failure of beams.

and b are applied in example structures and the mechanisms of progressive collapse are compared.

2.4. Analytical modeling of sudden removal of a column

The progressive collapse is generally initiated by a sudden loss of one or many structural members. Once a structural member (usually a column in the first story) is suddenly removed, the stiffness matrix of the system also needs to be suddenly changed. This may cause difficulty in the analytical modeling process. To avoid this problem, all member forces are obtained first from the structural model subjected to the applied load; then the structure is re-modeled without a column with its member forces (P, V, and M) applied to the structure as lumped forces to maintain equilibrium position (Fig. 4a and b); the structure becomes stable at time t_1 and the member force is suddenly removed at time t_2 to initiate progressive collapse. In this way the progressive collapse analysis starts from the moment that the structure is already deformed by the applied load, which reflects the loading situation quite realistically.

3. Integrated system for progressive collapse analysis

The main purpose of this study is to develop the integrated system for progressive collapse analysis based on the two major guidelines (GSA and DoD). The integrated system supports all the processes associated with progressive collapse analysis including modeling of structures, input of failure criteria, iterative nonlinear analysis, evaluation of damage indices, automatic generation of modified analytical models, graphic simulation of progressive collapse, etc. Fig. 5 shows the main flow of the integrated system divided into three parts; i.e. general modeling, special information for progressive collapse analysis, and progressive collapse analysis control program. In the integrated system developed, the general

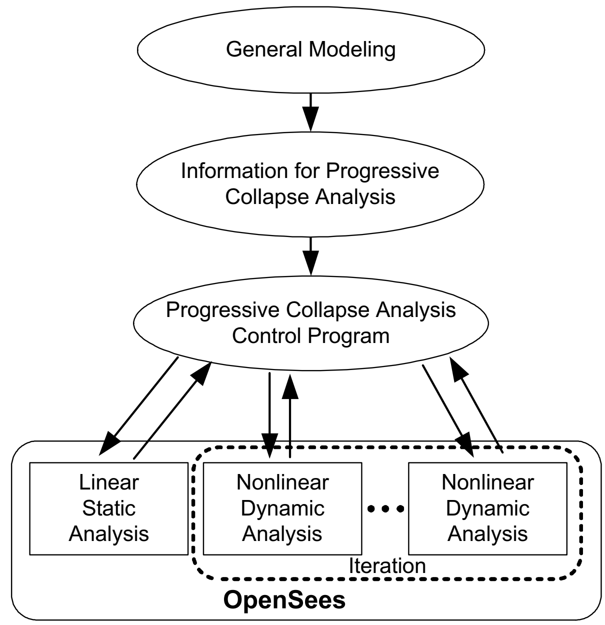


Fig. 5. Concept of the integrated system for progressive collapse analysis.

modeling for material properties, geometric configuration, loads, boundary conditions, etc. is the first step like other general-purpose structural analysis softwares. The pre-processor developed for convenience of the modeling effort is shown in Figs. 6 and 7. Several input dialog boxes for nonlinear materials provided in the OpenSees are presented in Fig. 6. The pre-processor displays the geometry of a structure, assigned loads, boundary conditions, sections and material properties as shown in Fig. 7. Since this pre-processor generates an input data file for the OpenSees, it also can be used independently as a pre-processor for the OpenSees.

The flow chart of the integrated system is presented in Fig. 8. After general modeling of a structure using the pre-processor, special information for progressive collapse analysis, such as the lost members, the types of damage index and parameters, nonlinear material properties, failure limit criteria, etc., are inputted. The integrated system performs linear-elastic static analysis using the input file for the OpenSees generated by the pre-processor to compute member forces. Since progressive collapse caused by abnormal load is an unusual event occurring under service load, unfactored loads are generally used and the strength reduction factors are ignored in the analysis. The analysis for progressive collapse starts with sudden removal of a critical structural member (a first story column in the GSA and DoD guidelines). The integrated system extracts the member forces of the removed mem-

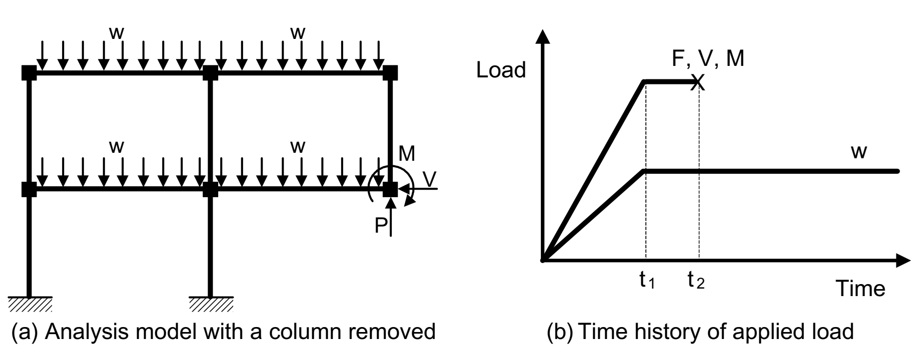


Fig. 4. Modeling of sudden removal of a column.

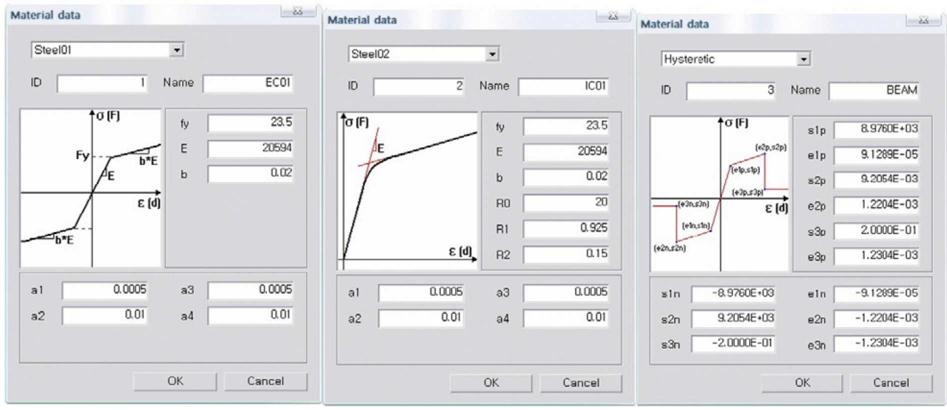


Fig. 6. Input dialog box for material properties.

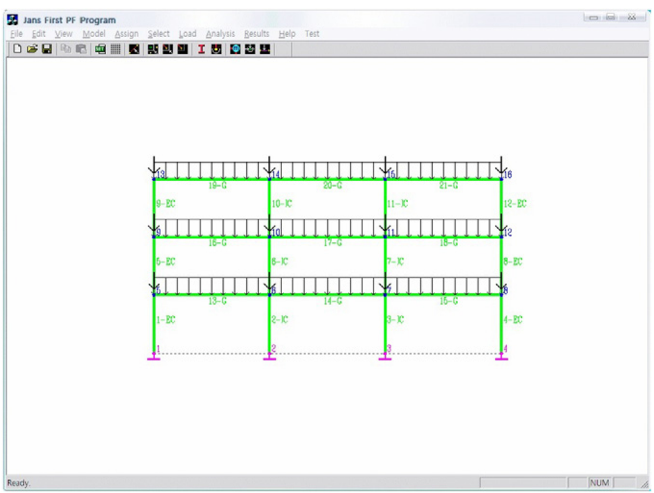


Fig. 7. Pre-processor for the integrated system.

bers. To make the structure with a critical member removed be at rest in its original configuration at first, the extracted internal forces are externally applied to the analytical model and stabilize the structure. Progressive collapse analysis starts with sudden elimination of these external forces to simulate sudden removal of members. After nonlinear dynamic analysis, the integrated system evaluates the damage indices of all structural members. If the damage index of any structural member reaches 1.0, the integrated system automatically removes the failed member and generates new analytical model for the next nonlinear dynamic analysis step. This procedure continues until there is no further member failure or until the structure becomes unstable and collapses progressively. In this analysis procedure using the integrated system, the strength and stiffness degradation of partially damaged members are considered by nonlinear material models as shown in Fig. 2. The strength and stiffness parameters are appropriately controlled by an engineer based on the properties of structural members.

This progressive collapse analysis process following the GSA or DoD guidelines may be performed manually by using a general-purpose structural analysis program. In this case, however, an engineer is required to trace the member forces and damage indices of all structural members at every time step, to make new analytical model with the failed members eliminated, and to carry out iterative analysis consecutively. The efficiency of this manual operation for progressive collapse analysis will be decreased and the possibility of operation errors may be increased as the building structure under consideration becomes taller or larger. For tall

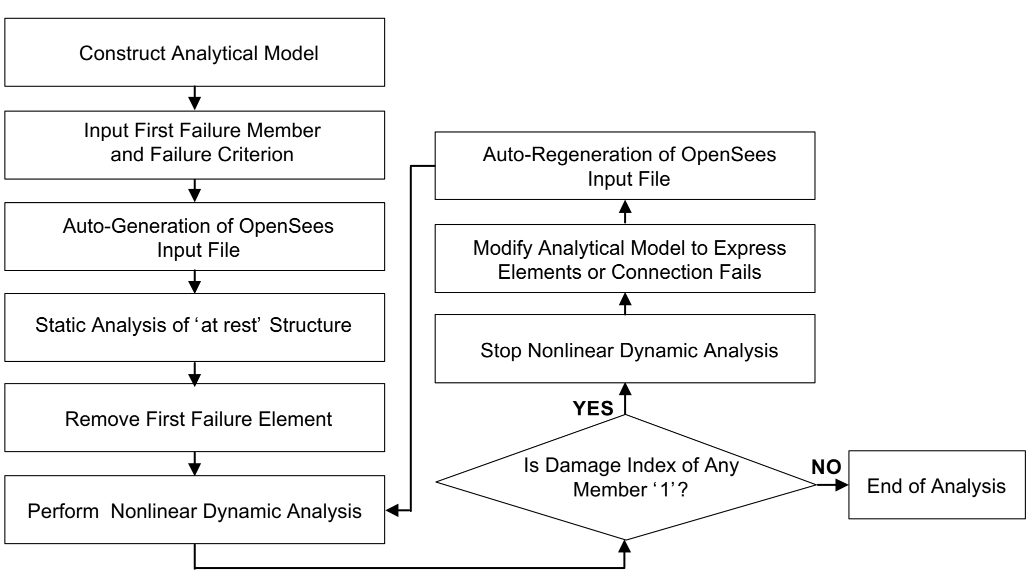


Fig. 8. Flow chart for progressive collapse analysis.

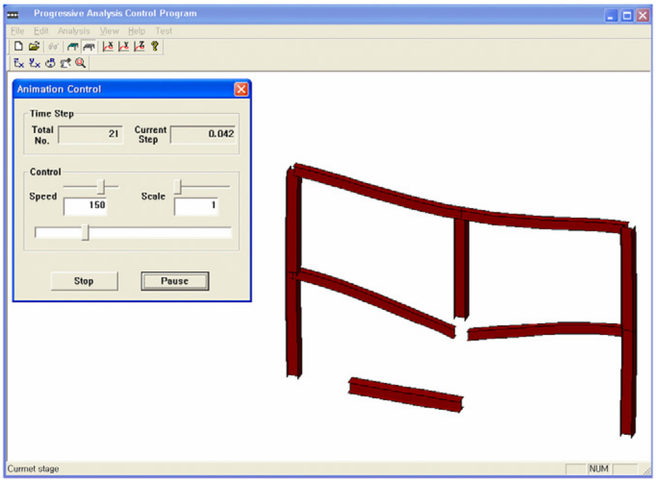


Fig. 9. Post-processor for displaying failure modes.

building structures with thousands of structural elements, in which prevention of progressive collapse is most important, to carry out the iterative procedure manually with a general-purpose analysis program may be practically impossible. The integrated system developed in this study is expected to solve this problem. The analytical results are extracted by the integrated system to simulate the progressive collapse process by a post-processor with a graphic animator as shown in Fig. 9. The graphic animator can present the damage level or plastic hinge rotation of each structural member at every time step by the size and color of circle indicators. It also may help an engineer to clearly understand the mechanism of progressive collapse and develop alternative design schemes to decrease the potential for progressive collapse. One of the primary purposes of this study is to develop the integrated system for progressive collapse analysis to raise work efficiency of practicing engineers. By employing the integrated system, progressive collapse potential of building structures may be conveniently investigated without complicated and repetitive procedures.

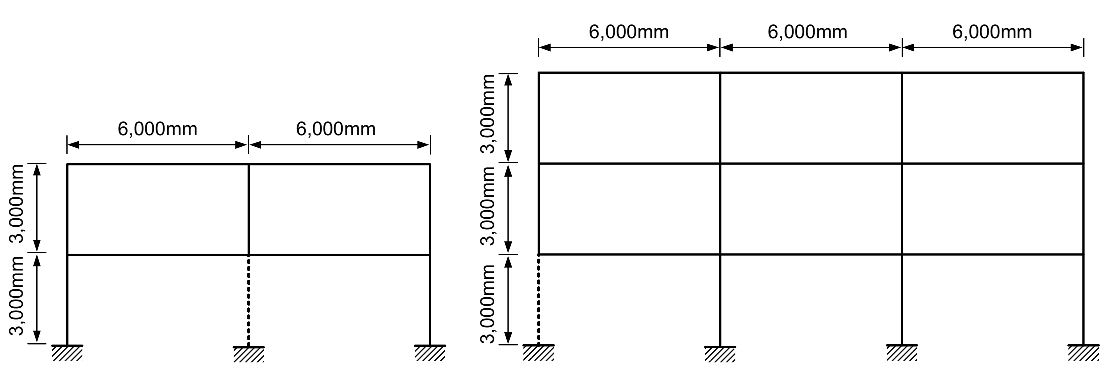
4. Numerical examples

Using the integrated system the 2- and 3-story framed structures shown in Fig. 10 were analyzed for progressive collapse. Although the integrated system is capable of analyzing 3-dimensional structures, nonlinear dynamic analysis of a 3-dimensional structure is very time-consuming. Thus, only 2-dimensional planar frames were used for numerical examples. The structures have 3 m story height and 6 m span length. The beams and columns are made of SM490 (F_y = 325 MPa) and SS400 (F_y = 235 MPa) steel, respectively, and were modeled by the Nonlinear Beam-Column element in the OpenSees. The member sizes are presented in Table 1. The dead and live loads of 0.15 kN/cm and 0.075 kN/cm, respectively, were imposed on the structures. The time interval for dynamic analysis was set to 0.005 s. As shown in Fig. 10 the internal column and the external column of the first story were removed from the 2- and the 3-story structures, respectively, to initiate progressive collapse. In this study a structural member was considered as failed, i.e. the damage index became 1.0, when its plastic rotation reached 0.035 based on the GSA and the DoD guidelines, which is larger than 0.02, the collapse prevention limit state for seismic load of return period of 2400 years suggested in the FEMA-365 [20].

Using the integrated system the model structures were analyzed to investigate their progressive collapse potential, and the analysis results were depicted in Figs. 11–13. Two different modeling techniques of failed members (Fig. 3a and b) and two different analysis methods (nonlinear static and dynamic analyses) were applied. Fig. 11 shows the locations of hinges in the 2-story frame formed by sudden removal of the first story internal column. Nonlinear static pushdown analyses were carried out to obtain the member-end rotations, and the member ends with their plastic rotations exceeding 0.035 (i.e. damage index of 1.0) were modeled as hinges as shown in Fig. 3a. Fig. 11a–c show the order of hinge formation, where it can be observed that hinges formed first at the ends of the second floor beams located on both sides of the removed 1-story column. This led to damage in the beam ends connected to the second story interior column, and finally to failure of all beam ends. No damage was observed in columns. Fig. 12 shows the results of nonlinear dynamic analysis, in which the failed members were treated the same way as the previous case. It can be observed that in the first phase hinges formed at both ends of the second story beams and at near ends of the roof beams connected to the internal column. Then damage spread to the upper ends of the second story external columns and finally to the far ends of the roof story beams. The hinge formation in columns, which was not observed in the nonlinear static analysis, resulted from dy-

Table 1
Member size of model structures

Member	2-Story	3-Story
Girders	H 250 × 130 × 6 × 10	H 250 × 125 × 7 × 11
Ext. columns	H 150 × 150 × 7 × 10	H 175 × 175 × 7.5 × 11
Int. columns	H 200 × 200 × 8 × 12	H 250 × 250 × 9 × 14



(a) 2-story structure (b) 3-story structure

Fig. 10. Model structures for analysis.

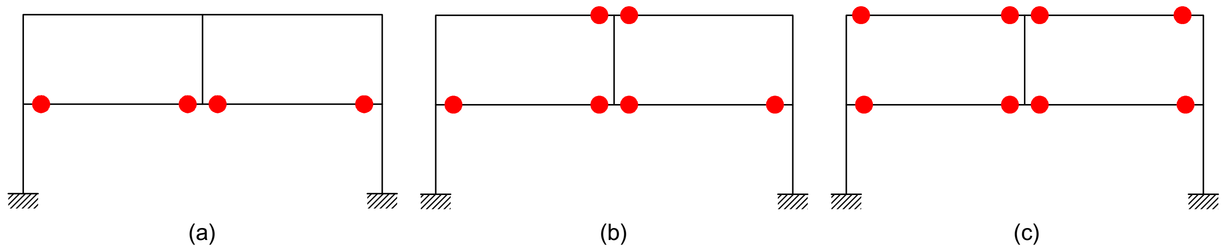


Fig. 11. Hinge locations obtained from nonlinear static pushdown analyses (failed members were not disconnected).

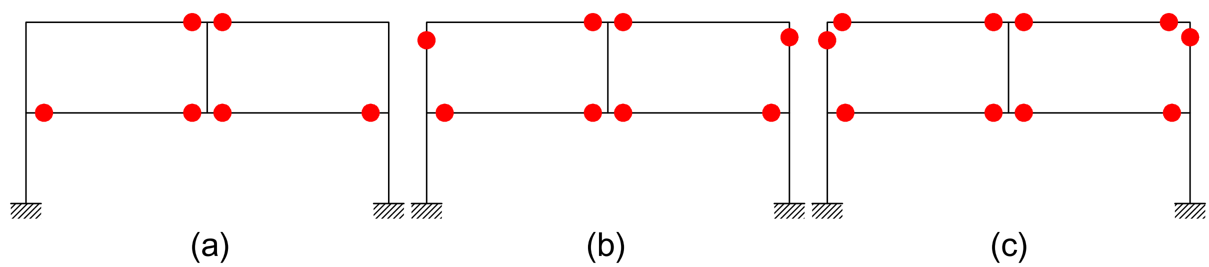


Fig. 12. Hinge locations obtained from nonlinear dynamic analyses (failed members were not disconnected).

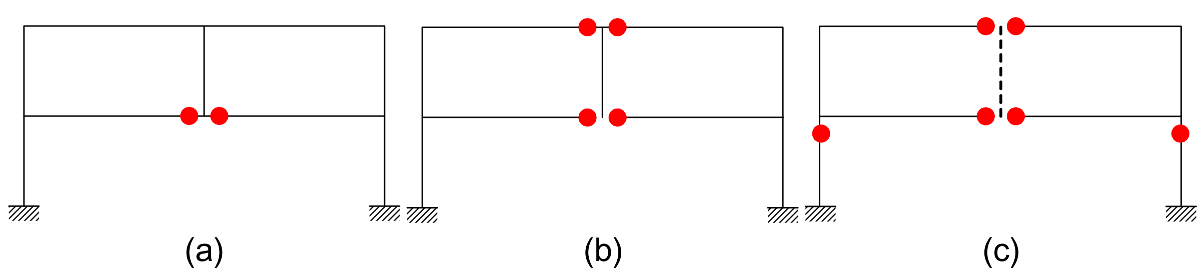


Fig. 13. Hinge locations obtained from nonlinear dynamic analyses (failed members were disconnected).

namic effect of impact load. Fig. 13 presents the results of the nonlinear dynamic analysis, except that new nodal points were added at the ends of failed members to disconnect them from the joints before the structure was reanalyzed as shown in Fig. 3b. In this way the participation of failed beams by catenary action is prevented and at the same time the GSA and the DoD guidelines are satisfied. Fig. 13a depicts that hinges first formed at near ends of the second story beams connected to the lost column. Then the failed beam ends were separated from the joint and the modified structure was analyzed again for progressive collapse. The analysis resulted in the hinge formation in the roof story beams (Fig. 13b), which led to the separation of the roof beams from the second story internal column. Then the second story internal column was removed from the model because all of its support failed. Finally hinges formed in the first story external columns and the analysis was terminated. The analysis results show that the collapse mechanism for progressive collapse depends greatly on the modeling technique for failed members and analysis methods applied (static or dynamic analysis).

To investigate the dynamic effect involved in the progressive collapse, the 3-story three-bay frame shown in Fig. 14 was analyzed by nonlinear static and dynamic analyses. The external column in the first story was removed and the rotations at points 1–9 and the vertical deflection at point *A* computed by static and dynamic analyses were compared in Table 2. In the nonlinear static analysis the vertical load was gradually applied at point *A* until the service load imposed on the removed column was reached. It can be observed in the table that as a result of static analysis

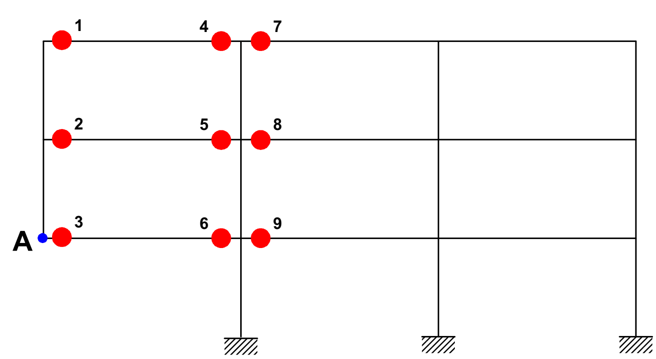


Fig. 14. Hinge formation in the 3-story model structure.

Table 2
Comparison of nonlinear static and dynamic analysis results (unit: rad, cm)

Responses	Static analysis (*a*)	Dynamic analysis (*b*)	(*b*)/(*a*)
Plastic rotation (point 1)	0.003	0.020	6.67
Plastic rotation (point 2)	0.011	0.032	2.91
Plastic rotation (point 3)	0.003	0.018	6.00
Plastic rotation (point 4)	0.010	0.032	3.20
Plastic rotation (point 5)	0.011	0.032	2.91
Plastic rotation (point 6)	0.012	0.050	4.17
Plastic rotation (point 7)	0.003	0.003	1.00
Plastic rotation (point 8)	0.003	0.001	0.33
Plastic rotation (point 9)	0.003	0.003	1.00
Vertical disp. at point *A*	16.00	30.85	1.93

vertical displacement of 16 cm occurred at point *A* and plastic rotations at all 9 points were less than 0.035 rad specified in the guidelines. However dynamic analysis resulted in plastic rotation of 0.05 rad at point 6 which is larger than the given failure criterion. To take the dynamic effect into account the GSA and DoD guidelines specify load factor of two for static analysis. It can be observed in the table that the deflection in point *A* obtained by dynamic analysis is 1.9 times that obtained by static analysis. The rotation angles computed by dynamic analyses ranged from 0.33 to 6.67 times those obtained by static analyses. Especially the rotation angles of the beams located in the bay in which the column was removed obtained by dynamic analyses were approximately three to six times larger than those obtained by static analyses. This implies that the static analysis with a load factor of 2 to consider dynamic effect may lead to unconservative results. Therefore, nonlinear dynamic analysis procedure would be needed to obtain reliable results for progressive collapse. The integrated system developed in this study enables engineers to carry out complicated nonlinear dynamic analysis for progressive collapse without difficulty.

5. Conclusions

In this study the integrated system for progressive collapse analysis has been developed to automatically evaluate the damage level of every member and to construct the modified structural model for next analysis step. To save time and effort to develop complicated solver, the existing nonlinear analysis program code OpenSees was used as a finite element solver in the integrated system for progressive collapse analysis. The developed integrated system includes a pre-processor with intuitive graphic user interfaces and a post-processor that can simulate the progressive collapse by 3D graphic animation. Using the integrated system, example structures subjected to sudden column failure were analyzed for progressive collapse. The graphic user interface and the post-processor developed in this study are expected to help engineers to carry out dynamic analysis using various modeling techniques and to compare failure mechanisms. Therefore the progressive collapse potential and collapse mechanism of building structures can be conveniently evaluated more accurately with significantly reduced time and effort.

The analysis results showed that the dynamic amplification could be much larger than two, which is specified for static analysis in the GSA and the DoD guidelines. This implies that dynamic analysis might be necessary to guarantee safety for progressive collapse caused by sudden removal of a column. The analysis results also showed that the collapse mechanism for progressive collapse depends greatly on the modeling technique for failed members.

Acknowledgement

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