Research on Catenary Action of Frame Structure in Progressive Collapse with Fiber Model

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Abstract. An advanced finite element model (FEM) is presented with fiber beam-column element of OpenSees in this study. Using this FEM, non-linear static push-down analysis of a steel frame structure was carried out by the alternate load path method, with two different cases that two different columns are removed respectively. Comparison analysis indicate that catenary action can be development in the case of middle column removal only, which is not developed after side column is removed. The reason for development of catenary action is that obvious axial tension force should be created in beams within damaged bay.

Introduction

Progressive collapse refers to the phenomenon that local damage of structural elements caused by abnormal loads results in global collapse of the structure[1]. Considerable attention has been focused on the phenomenon of progressive collapse[2,3,4] after the collapse of the Ronan Point apartment building in 1968.

There are two different approaches used for resisting the occurrence of progressive collapse in structural codes[5,6], namely the indirect method and the direct methods. With indirect method, little additional structural analysis is required by the designer. In general, the designer may use an implicit design that incorporates measures to increase the overall robustness of the structure. However, the direct method aims to enhancing the ability of structure to bridge across the local failure zone through using the resistance of catenary action. Since a few investigation were carried out to evaluate this resistance mechanism of progressive collapse [7], the research on this issue was not enough and systematic, and the reason for occurrence mechanism of catenary action is not clear.

Progressive collapse phenomenon is also an event including both geometric and material nonlinear behavior. Usually, a simplified model named lumped plasticity model, is used to account for the inelastic behavior of beam or column in steel frame analysis. But this model can not account for the spread of plasticity along members, and is not capable of capturing the interaction between moments and axial force in columns or beams. So far, the limited studies has been presented for the progressive collapse analysis based on the lumped plasticity model, which could not give a further research on catenary action.

In this study, an analytical model consisting of fiber elements, inherently including the interaction between axial force and moment, is built to further explore the centenary action resistance mechanism of the structure against progressive collapse. The numerical analysis model is based on the push-down analytical method by removing a column in various locations. And the reason for occurrence mechanism of catenary action is investigated.

Model for Progressive Collapse Analysis

Fiber Model. The beam-column elements in a structure are modeled using displacement-based elements with multiple integration points along the length of the element. Nonlinear behavior is characterized at the material level through a fiber discretization of the member cross section at integration points while a co-rotational formulation enables to consider large displacements and rotations. This fiber model is also capable of capturing the interaction between moments and axial loads during progressive collapse analysis. The fiber beam-column element is shown in Fig.1 for a local reference system.

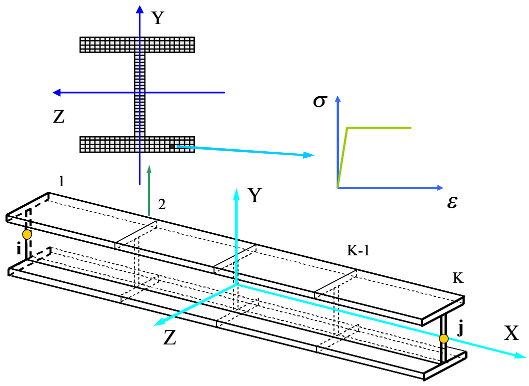


Fig.1 Fiber beam-column element

In this study, the performance of the structure subjected to local damage is investigated by the nonlinear analysis using the program code OpenSees. This program does not provide visualized Pre-processor and Post-processor for creating the finite element model and displaying the calculated results, which could be a barrier to practical applications of this program code. To deal with this problem, an interface macro-file, programmed by APDL language embedded in ANSYS, is presented in this study. With this macro file, the process of generating the FEA model and the display of the FEA results could be carried out on the platform of ANSYS, and then the calculating process on the platform of OpenSees code.

Prototype Structure. A representative ten-story planar steel frame structure, shown in Fig.2, is selected for the following analysis. This steel frame is designed, corresponding to Site Class II and Seismic Design Group I, as well as the seismic intensity degree 7 according to Chinese seismic design code. The steel frame structure has the six bays with the same span of 8.5m, and the story height is 4.8m for the first story and 4.0m for the others. The dead load, 4.8kN/m^2, consists of the self-weight of the slab, while the design live load is assumed to be 2.0kN/m^2.In the FEA model, the beams and columns are modeled using the fiber element with co-rotational geometric transformation and four integration points along the element length. Bilinear material model is used for modeling steel material, whose yield strength is 345MPa and modulus of elasticity is assumed to be 2.0×10^{5}MPa. Eventually, the entire frame model consists of 805 fiber elements and 1557 nodes.

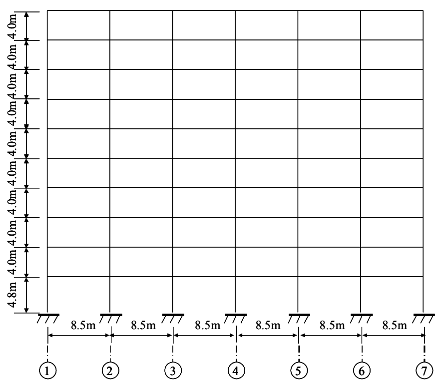


Fig.2 Ten-story steel frame structure

Analytical Method and Column Removal Conditions.

In this study, Pushdown analysis is adopted following the alternate load path method recommended by the GSA2003[8]. During the pushdown analysis, the gravity load is increased proportionally in the damaged bays, whereas the remaining part of structure is only subjected to nominal gravity loads (P_0), defined as,

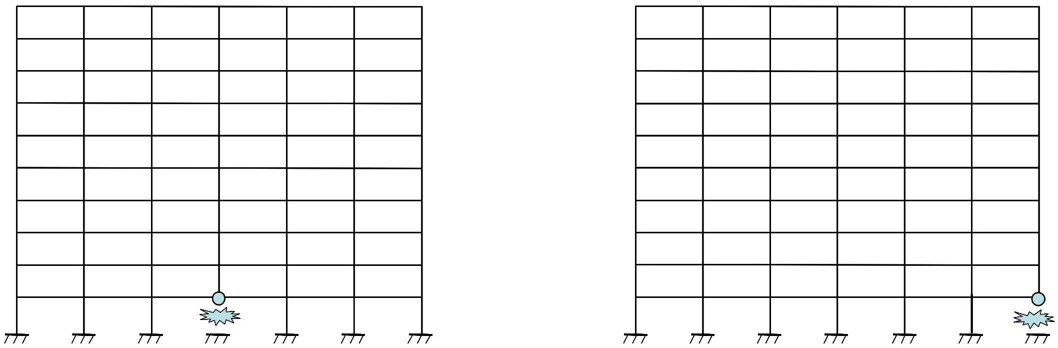
$$P_0 = 1.0P_D + 0.25P_L \quad (1)$$

where, P_D and P_L are dead and live loads respectively. The overloading capacity of the damaged structure is expressed in terms of the overload factor (P_{fac}), defined as the ratio between the failure load and the nominal gravity load,

$$P_{fac} = P_{failure} / P_0 \quad (2)$$

where, $P_{failure}$ is failure load.

Here, two different column loss conditions are considered to investigate the resistance mechanism of steel frame. As shown in Fig. 3, the middle column removal of the first story is as Case 1 and the side column removal as Case 2.



(a) Case1: the middle column removal in the first story (b) Case 2: the side column removal in the first story

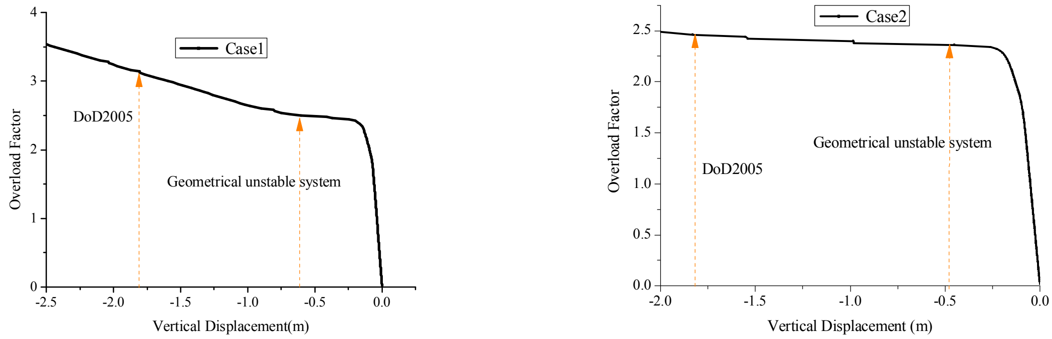
Fig. 3. The cases in the study

Comparison Analysis of Different Column Removal Conditions.

Fig.4 shows the variations of vertical displacement in Case 1 and Case2, as a function of overload factor (P_{fac}). In the initial stage of applying vertical loading, vertical displacement varies linearly with the increase of the overload factor value both in Case1 and in Case2. When the overload factor value increases to 1.80 for Case1 and 1.82 for Case2, the yielding phenomenon occurs in the damaged frame; meanwhile, the tangent stiffness decreases as the overload factor increases. When the steel frame structure in the damaged bay forms a geometrical unstable system, which indicates that all the ends of beams form the plastic hinges in the damaged bay as shown in Fig.5, bending resistance mechanism is out of work.

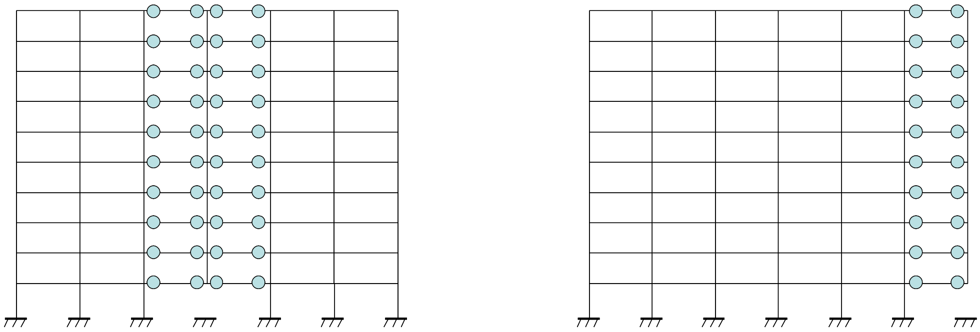
The difference between Case1 and Case2 is that with the increase of the structural deflection, the structural stiffness increases again in Case1, which means that the residual structure can continue to bear load, but in Case2 the structural stiffness almost keeps unchanged, which indicates that the residual structure can not bear vertical load. It implies that the additional load could be carried with the catenary action in Case 1 after the bending resistance action lost efficacy.

When the rotation of beam in damaged bay reaches the limitation defined as DoD2005[9] which means that the disproportionate collapse may be induced, the overload factor value in Case1 reaches 3.14 which is 1.28 times greater than that corresponding to the bending resistance, but in Case2 the overload factor value is 2.36 which is almost not increasing after geometrical unstable system occurs. From analysis above, in the condition of the middle column removal in the first story, catenary action can be developed, but in Case2 not.



(a) Case1 (b) Case2

Fig.4 The overload factor-vertical displacement relationship in Case1 and in Case2

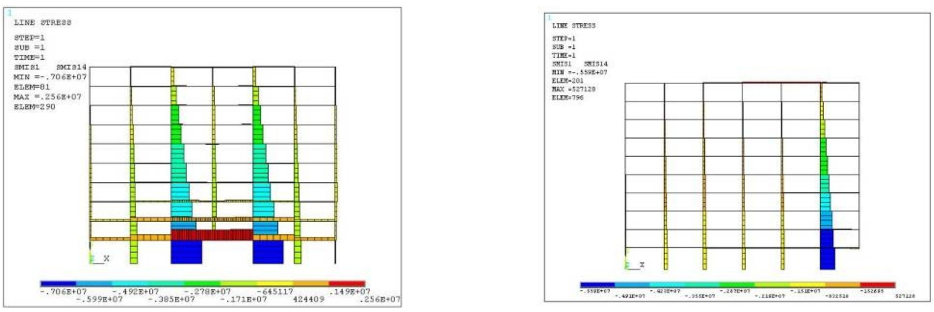


(a) Case1 (b) Case2

Fig.5 The geometrical unstable system in the damaged in Case1 and in Case2

Axial force Analysis of Beams in Damaged Bay

Fig.6 shows the axial force diagrams of residual structure in Case1 and in Case2. It could be seen that obvious axial tension force is developed in beams on the top of the removal column in Case1. And very small axial tension force which almost can be neglected is developed in Case2. Fig.7 shows axial force -vertical displacement relationship of each floor beam in damaged bay of Case1. It can be seen that only the first to the third floor beam have the obvious axial force, and others beams create axial force which can be almost neglected. Above all, the main factor, which lead to the development of catenary action, is occurrence of axial force in beams, which can not be ignored within the damaged bay.



(a) Case1 (b) Case2

Fig.6 Axial force diagrams of residual structure in Case1 and in Case2

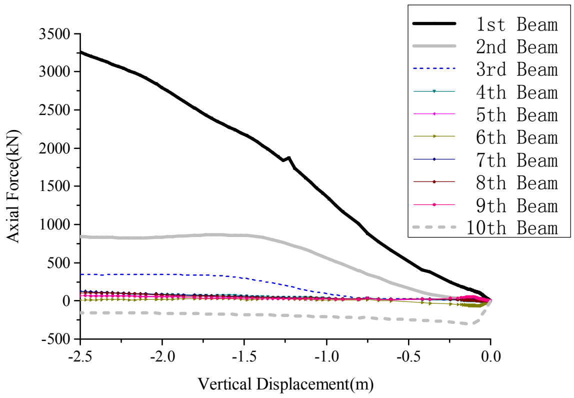


Fig.7 Axial force -vertical displacement relationship of each floor beam in damaged bay of Case1

Conclusions

In this study, an advanced finite element model is built based on fiber beam-column element, aiming at reveal the progressive collapse resistance mechanism of the steel frame structure. With this model, non-linear static push down analysis of a ten-story structure, in two different cases of column removal, is conducted following the alternate load path method recommended by the GSA2003. The analytical results are concluded as:

(1) The residual structure has the different resistance mechanisms in the different cases of column removal. In the initial stage, the bending resistance mechanism can provide the dominate resistance capacity against the structural progressive collapse in both cases of middle and side column removal. However, after the bending resistance mechanism is out of work, the catenary action is only induced in the case of the middle column removal, which is not developed in the case of the side column removal.

(2) Comparison analysis shows that obvious axial tension force is developed in beams on the top of the removal column in the case of middle column removal, but not in the case of side column removal. The main factor leading to the development of catenary action, is the occurrence of axial force in beams, which can not be ignored, within the damaged bay.

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