Nonlinear Simulation Analysis of RC Frame Beam Slab Column Spatial Synergy against Progressive Collapse Performance under Failure of Bottom Corner Columns

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Abstract. In this paper, three-dimensional degenerated virtual laminated element nonlinear finite element method is utilized to simulate the whole process of vertical anti-continuous collapse of ten-storey RC frame structure with nine-palace lattice under the failure of the bottom corner columns. It can be found that the axial force redistribution of the same story column shows relationship with the load range and the distance from the failure column. Besides, the integral collapse resistance mechanism and the axial force of the vertical column of the failure column are different from that before failure.

1. Introduction

Finite element method is defined as a widely used and reliable numerical analysis approach. The analysis method based on entity element requires numerous units and has low computational efficiency; the approach on the basic of the fiber element needs small number of elements, but is difficult to simulate the effect of transverse reinforcement (stirrups); as the elastoplastic analysis method based on member element can analyze large-scale spatial structures efficiently, it cannot simulate the material nonlinearity perfectly. Nonlinear finite element method on the basic of degenerated three-dimensional solid virtual laminated element can simulate geometric nonlinearity and material nonlinearity well, with small number of elements and efficient calculation. In the present work, three-dimensional degenerated virtual laminated element nonlinear finite element method is utilized to simulate the spatial cooperative effect of beam-slab-column structure with the consideration of geometric and material nonlinearity. Through simulation analysis, the thorough deformation, load-displacement relationship and axial force redistribution mechanism of the ten-storey RC frame structure with the bottom corner columns removed are revealed.

2. Introduction of degenerated three-dimensional solid virtual laminated element and method used in this paper

Based on the isoparametric element of three-dimensional solid, the degenerate element of
three-dimensional solid is acquired by modifying the elastic coefficient matrix, introducing relative displacement, or directly introducing a series of basic assumptions such as beam, plate, shell, membrane, et al. Such element has only linear degree of freedom and no angular degree of freedom, which can realize fine connection between elements, can consider the shear effect in all directions, and accurately analyze the torsional and warping effects of the structure, meanwhile avoid the concept of neutral axis and neutral surface. By introducing the concepts of virtual node and virtual material area, different geometric information and material attributes can exist in the same element. The non-entity area is defined as zero, a degenerate virtual laminated element of three-dimensional entity is formed, which breaks through the limitation that various materials should be divided into different elements. In addition, three-dimensional degenerate virtual laminated element approach adopts the Lagrange scheme [1] (T.L. method) to analyze the ultimate bearing capacity in geometric nonlinearity. In the aspect of material nonlinearity, concrete materials use Ohtani and Chen's multi-axial strengthening plastic model, that can well predict the plastic volume change, considering the influence of tension-compression zone, the ratio of tension stress to compression stress on plastic deformation. The concrete crack adopts an orthogonal distribution crack model to consider multi directions cracking at an integral point. The failure condition of three-parameter strengthened plastic model defined by Ohtani and Chen is adopted to define the failure criterion of concrete. The failure requires the concrete strain to reach the ultimate strain, in which concrete with three-dimensional cracking is included. Furthermore, the shape and displacement of reinforcement are described by 3 node one dimension isoparametric element. Nonlinear equations are solved by mN-R iterative incremental method, and loads are applied by the step stiffness parameter method [4]. Generally speaking, nonlinear finite element method based on degraded three-dimensional solid virtual laminated element can well analyze the simulation of spatial cooperative work of beam-slab-column wall.

3. Nonlinear simulation analysis for spatial synergistic collapse resistance mechanism of beams, slabs and columns with failure of bottom side columns in high-rise RC frame structure

3.1 Model design and simulation analysis
According to Chinese specifications, a ten-storey (15m × 15m RC) spatial frame structure with a height of 3.6m is designed. The section size of the columns is 500mm × 500mm. And the cross sections of the beams are 250mm × 500mm. The thickness of the plates is 120mm. Furthermore, frame columns, beams and cast-in-situ floor slabs are all made of concrete of strength grade C30, and HRB400 steel bars are employed for longitudinal reinforcement and floor reinforcement of beams and columns. The load on the beams, as well as the dead and live load on the floor are considered according to the functions and general conditions of the office buildings. The standard values of floor constant load and live load are 1.5kN/m² and 2.0kN/m², respectively. The model sets the seismic fortification intensity of 7 degrees (design basic earthquake acceleration value 0.1g), in class II site, designs earthquake grouped into the first group, the seismic grade of the frame is magnitude 4. The basic wind pressure is 0.45kN/m². To facilitate the study without considering the layout of balconies, toilets and stairs, it is assumed that the bottom frame columns are embedded in the ground. To facilitate the analysis, the layouts of balconies, toilets and stairs are not considered, and the bottom frame columns is assumed to be embedded in the ground. With PKPM software modeling as well as the calculation and analysis in SATWE, the reinforcement information of the model is acquired. The demolition member method is utilized here to model the demolished bottom corner column Z1 (position shown in Fig. 1) by three-dimensional entity degenerated virtual laminated element nonlinear finite element method. According to the actual reinforcement of SATWE, the floor dead and live load are applied at one time, and the failure force is gradually introduced by the “step stiffness method”. The structural plane dimension, component number and model finite element plane diagram are shown in Fig. 1. The spatial finite element steel bar layout is demonstrated in Fig. 2.
3.2 Model failure process and morphology

With nonlinear finite element analysis of degenerated virtual laminated elements using three-dimensional solid elements, the vertical displacement diagram (Fig. 3), deformation diagram (Fig. 4) and displacement contour diagram (Fig. 5) are obtained. During the loading process of the model, the unique girder lattice plate B1 (see Fig. 1) supported directly by Z1, deforms to the failure column Z1 under the cooperation of beam and plate, and the plate acts as a membrane mechanism. The edge beams (XL1, YL1) and B1 join together to resist collapse. A 1/8 spherical deformation morphology is formed, which leads to obvious tensile failure at the joint of B1 and surrounding beams. In addition, serious torsional deformation happens to XL1 and YL1. The failure of the bottom corner column results in the falling of whole upper 2-10 stories, and the deformation of the beam, slab and column increases synchronously at the corresponding vertical position. The vertical displacement variation of the beam-slab synergistic deformation can be clearly observed in Fig. 5. Herein, the maximum displacement point of the almost failure structure takes place at B1. Combined with the load-displacement curve before and after the failure of the corner column (Fig. 6), where the solid line corresponds to the load-displacement curve before the failure (i.e. loading simulated according to the original complete model), and the dotted line means the load-displacement curve after the failure (the same below). Before the failure of the corner column and when the load does not reach 4.8kN/mm², the displacement increment of the plate and the failure column is basically equal. After reaching 4.8kN/mm², the displacement increases rapidly, and the maximum vertical displacement appears at the center of the plate (i.e. the plate yields first), and the vertical displacement of the four plates tends to be similar. After the failure of the corner column, the vertical displacement rate is much larger than that before Z1 failure. With the rise of floor live load, the load-displacement curve of "orthogonal L-shaped beam" tendons yielding in the failure zone of corner columns and the initial appearance of plastic hinge of beams obviously changes. However, because of the participation of floor slabs, the overall stiffness of the structure shows a steep drop but stays relatively stable. From the initial appearance of beam hinge to the ultimate state of bearing capacity, there is still obvious load in whole structure, which suggests that the increment of load fully demonstrates the real effect of the spatial co-operation between the beam, slab and column of the residual structure after the failure of the bottom corner column.
3.3 Redistribution analysis of beam-slab-column spatial synergistic axial force

Observing the axial force of the bottom column before and after the failure of the corner column (Fig. 7), it can be seen that the axial force of the bottom corner column $Z_6 = Z_7 = Z_{11} > Z_2 = Z_3$ before the failure of $Z_1$, and the magnitude of the axial force of each column is related to the load range. While after the failure of the bottom corner column $Z_1$, the increase of axial force of each column is $Z_2 > Z_6 > Z_3 > Z_{11} = Z_7$. The axial force of each column and the amplitude of axial force increase degree after the failure of angle column depend on the load range and the distance away from the failure column. More specifically, the larger the load range is, the closer the distance to the failure column is; the greater the axial force is, more the amplitude of axial force increases. As shown in Fig. 8, 9 about the axial force of $Z_2$ vertical coaxial columns before and after the failure of the corner columns, the curve turns when the load is applied to 23.46kN/mm². When the load increases to 24.21kN/mm² ("L-shaped beam" longitudinal bars yield, beam hinges appear), the axial force of some columns
converts from pressure to tension. After the failure of the angle column, the axial force of the fifth storey is the largest. The axial force of the columns below the fifth storey increases from bottom to top, while the one above the fifth storey decreases from bottom to top, which indicates the mode of force transmission and the overall collapse resistance mechanism of the new space beam-slab-column structure system formed after the failure of the angle column.

4. Conclusion

After the simulation analysis of spatial synergistic collapse resistance of beam, slab and column with corner column failure in the bottom floor of ten-storey RC frame structure with three-dimensional degenerated virtual laminated element nonlinear analysis method, the conclusions can be drawn below:

(i). Three-dimensional degenerated virtual laminated element theory can simulate the spatial synergy among beam, slab and column perfectly, and demonstrates various benefits, such as fewer elements, high calculation efficiency and accurate calculation results.

(ii). Due to the spatial cooperative effect among beams, slabs and columns, the redistribution of axial force in the same story of RC frame columns after the failure of corner columns in the bottom floor of high-rise RC frame is that the axial force of each column and the amplitude of axial force increase degree after the failure of angle column depend on the load range and the distance away from the failure column. In other words, the larger the load range is, the closer the distance to the failure column is; the greater the axial force is, more the amplitude of axial force increases.

(iii). As the result of load transfer path changing, the axial pressure distribution of frame columns in the upper floors coaxial with the failure columns increases progressively from the bottom to the top 2-5 floors, while decreases progressively from 6-10 storey. As the load reaches a critical value, the axial pressure of each column will not increase with the load any more but decrease. Moreover, the axial force of each column will transfer from pressure to tension close to the failure, which fully suggests the coordinated vertical force transfer mode of beam-slab-column space and the overall collapse mechanism.
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References
[1] Hui-Fa, Chen; A. F. Sarip; Constitutive equation of concrete and soil[M]. Tian-Qing, Yu; Xun-Wen, Wang; Xi-La, Liu; etc. translate. Beijing: China Building Industry Press, 2004.
[2] Xu-Cheng, Wang; Min, Shao. Fundamental Principles and Numerical Methods of Finite Element Method[M]. Beijing: Tsinghua University Press, 1995.
[3] Bergan P G., Holand I and Soreide T H. Use of Current Stiffness Parameter in Solution of Nonlinear Problems, Energy Methods in Finite Element Analysis (Edited by R. Glowinski et al) John Wiley & Sons, 1979, 265-282.
[4] Yi-Gang, Jia; Huan, Li; Guang-Yu, Wu; Zhi-Jun, Yuan; Qing, Zhang. Spatial nonlinear simulation analysis of progressive collapse resistance of R. C. frame structure under different seismic precautionary[J]. vol. 34, no. 2, pp. 1013-1024, 2018
[5] G. Y. Wu, J. F. Wang, Y. Q. Xiang. et al. Computation of ultimate capacity of reinforced concrete box girders, Journal of Zhejiang University 41(1) (2007). 161-165.
[6] G. Y. Wu, W. Lin, J. F. Wang, et al., Influence of effective prestress on ultimate bearing capacity for large-span pre-stressed concrete bridge. Chinese Journal of Computational Mechanics 30(3)(2013). 362-369.
[7] Yi-Gang, Jia; Wen-Guo, Ren; Guang-Yu, Wu; Zhi-Jun, Yuan; Huan, Li; Nonlinear simulation analysis of seismic design effect of RC frame "strong column weak beam" considering beam-column space synergy effect[J]. Building Structure. 2017, 47(7): 43-51.
[8] L. Kwasniewski, Nonlinear dynamic simulations of progressive collapse for a multistory building, Engineering Structures 32(5) (2010), 1223—1235.
[9] M. H. Tsai, Analytical methodology for the dynamic amplification factor in progressive collapse evaluation of building structures, Mechanics Research Communications 37(1) (2010), 61—66.
[10] P. Song, L. Dagang and S. Cui, Reliability analysis of progressive collapse limit state of reinforced concrete frame structure under earthquakes, Journal of Building Structures 34(4) (2013), 15-22.