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3-D Nonlinear Dynamic progressive collapse Analysis of multi-storey steel composite frame buildings – parametric study

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Abstract

In order to obtain a better understanding of the full structural behavior of multi-storey building under progressive collapse, a 3-dimensional finite element model built by the author was used in this paper to analyze the progressive collapse of multi-storey steel composite frame building. The proposed model can represent the full 3-D behavior of the multi-storey building under the sudden column removal. Based on this model, parametric studies were carried out to investigate the structural behavior with variations in: strength of concrete, strength of structural steel, reinforcement mesh size, numbers of columns removed. Through the parametric study, the measures to mitigate progressive collapse in the future design were recommended.

Keywords: progressive collapse, connection, finite element, modelling

1 INTRODUCTION

The terminology of progressive collapse is defined as ‘the spread of an initial local

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failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it' [1]. After the event of 11 September 2001, more and more researchers started to refocus on the causes of progressive collapse in building structures. There are design procedures to mitigate the potential for progressive collapse in the design guidance of UK and US. In the United States the Department of Defense (DoD) [2] and the General Services Administration (GSA) [3] provide detailed information and guidelines regarding methodologies to resist progressive collapse of building structures. Both employ the alternate path method (APM). APM is a threat independent methodology, meaning that it does not consider the type of triggering event, but rather, considers building system response after the triggering event has destroyed critical structural members. If one component fails, alternate paths are available for the load and a general collapse does not occur. The methodology is generally applied in the context of a 'missing column' scenario to assess the potential for progressive collapse and used to check if a building can successfully absorb loss of a critical member. In U.K., The UK Building Regulations [4] and BS5950 [5] has led with requirements for the avoidance of disproportionate collapse.

In recent study, there are some experimental and analytical studies on the progressive collapse behaviors of buildings under the missing column scenario. Khandelwal et al [6] studied the progressive collapse resistance of seismically designed steel braced frames with validated two dimensional models. Two types of braced systems are considered: special concentrically braced frames and eccentrically braced frames. The simulation results show that the eccentrically braced frame is less vulnerable to progressive collapse than the special concentrically braced frame. Izzuddin et al [7][8], proposed a simplified framework for progressive collapse assessment of multi-storey buildings with sudden column loss scenario. It analyzed the nonlinear static response with dynamic effects evaluated in a simple method. Kim et al [9] studied the progressive collapse-resisting capacity of steel moment resisting frames using alternate path methods recommended in the GSA and DoD guidelines. The linear static and nonlinear dynamic analysis procedures were carried out for comparison. It was observed that the nonlinear dynamic analysis provided larger structural responses and the results varied more significantly. However the linear procedure provided a more conservative decision for progressive collapse potential of model structures. Paik et al [10] investigated the possibility of progressive collapse of a cold-formed steel framed structure. The results showed that the removal of corner wall columns appeared to cause progressive collapse of a portion of the second and third floor of the end bay directly associated with the column removal, and not the entire building. Using the commercial program SAP2000, Tsai et al [11] conducted the progressive collapse analysis following the linear static analysis procedure recommended by the US General Service Administration GSA .Yu et al [12] proposed a simplified model to perform progressive collapse analysis, parametric study were also conducted using their model.

Although there are some researches have been done as mentioned above, they are all based on bare steel frame without considering the floor systems. Most of them are 2-D models. Therefore, it is unrelated to real structural performance. Without considering the contribution of the slabs, the beneficial effects of such as compressive arching and catenaries actions are not clear. This will lead to the prediction of an unrealistically large damage area exceeding the prescribed limits. Therefore, more detailed research toward the progressive collapse of multi-storey building is timely. Using ABAQUS [13], Fu [14] proposed a full scale 3-D finite element model to simulate multi-storey building. The investigation of progressive collapse is conducted in the different column removal scenarios. Compared with two dimensional models, the model of Fu [14] could accurately monitor the overall structural behavior of the whole building.

In this paper, using the 3-D finite element modeling techniques developed by the Fu [14], 3-D finite element models representing 20 storey composite steel frame buildings with bracing system were built to perform the progressive collapse analysis.

The models accurately displayed the overall behavior of the 20 storey buildings under sudden loss of columns, which provided important information for additional design guidance on progressive collapse. Based on this model, parametric studies were carried out to investigate the structural behaviors of this type of buildings. Through the parametric study, the measures to mitigate progressive collapse in the future design were also recommended.

2 3D FINITE ELEMENT MODEL

As shown in Fig 1, a three-dimensional finite element models were created by Fu [14] using the ABAQUS package to conduct the progressive collapse study of the high-rise building. The models replicated the 20 storey buildings with the grid space of 7.5m in both directions as it is shown in Fig 2. The floor height is 3 m for each floor. The main lateral stability is provided by cross bracing also shown in Fig.1. The slab thickness are 130mm, the columns are British universal column UC356X406X634 from ground floor to level 6, UC356X406X467 for level 7to level 13, UC356X406X287 for level 14 to level 19, all the beams are British universal beam UB533X210X92. The cross bracings are British circular Hollow section CHCF 273X12.5. This model simulated the full structural framing of the typical high-rise buildings in the current construction industry with full composite action of the composite slab.

2.1 3D finite element Modeling technique

All the beams and columns are simulated using *BEAM elements. The structural beam elements are modelled close to the centreline of the main beam elements. The slab are simulated using the four node *Shell element. Reinforcement was represented in each shell element by defining the area of reinforcement at the appropriate depth of the cross-section using the *REBAR element from the ABAQUS library. This reinforcement is defined in both slab directions and was assumed to act as a smeared layer. The beam and shell elements are coupled together using rigid beam constraint equations to give the composite action between the beam elements and the concrete slab. The material properties of all the structural steel components were modelled using an elastic-plastic material model from ABAQUS [13] which incorporates the material nonlinearity. The concrete material was modelled using a concrete damage plasticity model from ABAQUS [13]. The tensile strength of the concrete is ignored after concrete cracking. The shell elements are integrated at 9 points across the section to ensure that the concrete cracking behaviour is correctly captured. The models are supported at the bottom as shown in Fig.1. The mesh representing the model has been studied and is sufficiently fine in the areas of interest to ensure that the developed forces can be accurately determined. The steel beam to column connections is assumed to be fully pinned. The continuity across the connection is maintained by the composite slab acting across the top of the connection. Therefore, the beam to column connection is more or less like a semi-rigid composite connection which is to simulate the characteristic of the connections in normal construction practice. Detailed modelling techniques were explained in Fu [14].

2.2 Validation of the model

In order to valid the proposed model, in Fu [14], a two storey composite steel frame ABAQUS model was built. The model replicated the full scale testing of a steel-concrete composite frame by Wang et al [15]. Comparison between the tests result and the modelling result is made. Good agreement is achieved.

3 PARAMETRIC STUDIES

The alternate path method (APM) is applied here to perform the progressive collapse checking of the existing 20 storey buildings. The resistance ability of the building under sudden column loss is assessed here using nonlinear dynamic analysis method with 3-D finite element technique. The loads are computed as dead loads (which is the self-weight of the floor) plus 25% of the live load in accordance with the acceptance criteria outlined in Table 2.1 of the GSA guidelines [3]. The columns to be removed are forcibly removed by instantaneously deleting them. Table 1 shows the list of analysis cases considered in this study together with the different parameters which were used in each case. To facilitate the following discussion, the columns and beams are named as follows according to the grid line shown in Fig2. For instance, Column C1 stands for the column at the junction of grid C and grid 1. Beam E1-D1 stand for the beam on grid 1 starting from grid E to grid D.

3.1 Effect of concrete strength

In order to evaluate the effect of concrete strength, three grades of concrete are chosen, which are C30, C40, C60 which are the typical concrete grade used in the current construction practice. The response like the vertical displacement, the major axis moment and the axial force are reordered. The comparison result is shown in Fig. 4 to 6. When the columns A1 as shown in Fig. 3 were suddenly removed, the node on the top of the removed column vibrated and reached a peak vertical displacement and eventually rest at displacement as shown in Fig. 4. The adjacent beam and column were initially overloaded and started deforming nonlinearly. The redistribution of forces was observed to take place as shown in Fig. 5 and 6. It can be noticed from the Fig5 and 6 that, the weaker the concrete strength, the greater the force in the steel beam, this is because for lower grade concrete strength, the concrete cracked more early than the higher grade concrete. Therefore, more force is taken by the steel member rather than the composite slabs.

It can be seen from the results that, generally, the grade of concrete does not have much influence on the structural behaviour of the buildings. From Fig.4 it can be seen that the tensile strength of the concrete has smaller effect on the deformation. The reason for this is that the joints and the steel beams have provided sufficient effective tying that prevents large deformation in the floors. This means increasing of the strength in the concrete has only marginal contribution to the effective tying of the system. The similar result has been found in the research of [12] as well.

3.2 Effect of reinforcement mesh

In order to evaluate the effect of steel mesh used in the concrete, four types of steel mesh were chosen, which are A142, A193, A252 and A393. They are the typical mesh size used in the current composite slab design. The comparison result is shown in Fig 7, 8 and 9. It can be seen that, when one column A1 was suddenly removed, the node on the top of the removed column vibrated and substantially reached a peak vertical displacement. The response eventually rest at displacement as shown in Fig. 7. The adjacent beam and column were initially overloaded and started deforming nonlinearly. A large redistribution of forces was observed to take place as shown in Fig. 8 and 9. The comparison result shows that, steel mesh size has smaller effect on the deformation under the one column removal scenarios. The reason is the same as it is discussed in section 3.1. Which can be further validated in Fig .8 and 9 which are the comparison of the bending moment and axial force of beam, it can be seen that the variation are quite small as most force are resistant by the steel beam, although there are some centenary resistance from the slab, the influence are quite small.

3.3 Effect of strength of Steel structural member------ one column removal scenario

In order to evaluate the effect of strength, three grades of steel members are chosen, which are S275, S355, S460. The comparison is show in Fig.10. It can be seen that, there is no much difference between these three cases. This is because the inspection of the model shows that no plastic strain were not developed in this three cases, as is it is shown in Fig.11. That means all the beams are still in the elastic stage, therefore the material strength are same, so, there are no obvious difference of the response.

The beams selected in this research are based on the British design code requirement to resist ultimate load combination 1.4DL+1.6LL. Therefore, it can also be concluded that beams normally have resilient capacity under the one column removal scenarios, if it is designed with ultimate load combination,

3.4 Effect of strength of Steel structural member ------ two columns

removal scenario

In order to further evaluate the effect of steel strength, two columns removal scenario was investigated as it is shown in Fig.12, where, two columns A1 and A2 at ground level were suddenly removed, as it is shown in Fig.13 that the plastic strain were developed in the steel beams. The comparison of the response of the models is shown in Fig.14, 15 and 16. It can be seen that, the less the steel member strength, the greater the vertical deflections and the higher the steel grade the higher bending moment and axial force were observed as well. This is because for these three cases, the structural steel member went to plastic stage, therefore, higher grade steel have higher capacity to absorb more energy caused from the column loss, hence, it exhibit less displacement. It can be concluded that, the higher the strength of the steel member, the higher the resistance to progressive collapse.

3.5 Effect of column loss-----comparison between one, two and three columns removal scenario

From above discussion and the discussion of Fu [14], it can be seen that, the building is more vulnerable to the removal of two columns. This is due to the larger affected loading area after the column removal which also determines the amount of energy needed to be absorbed by the remaining building. Therefore, it is worth performing an analysis under different two columns removal scenarios. The model chosen has C40 concrete, S355 steel and A252 mesh. In first case, column A1 was removed. In second case, column A1, A2 were removed. In the last case, as it is shown in Fig.17, column A1, A2 and B1 were removed. The columns removed are all on the ground level. Fig 18 is the comparisons of the response under these three different removal scenarios. The structure failed in the last case. For two columns removal scenario, due to larger affected area the vertical displacement is almost as twice as the one column removal scenario. The structure exhibit the capacity to resist one column removal scenario.

3.6 Measures to mitigate progressive collapse

From the extensive parametric study it can be seen that, for the multi-storey composite steel frame buildings, the effective way to mitigate the progressive collapse is to increase the strength of the steel structural members and the beam to column connections. As most force are resisted by the structural steel members rather than the composite slab.

It can be seen from section 3.5 that, the building is more vulnerable to the removal of more than two columns. As it is discussed by Fu [14], this is due to the larger affected loading area after the column removal which also determines the amount of energy needed to be absorbed by the remaining building. Therefore, another effective way to resist progressive collapse is to decrease the spacing of the grid or provide more redundancy in the structural scheme.

4 CONCLUSIONS

In this paper, the behaviour of the 20 storey steel composite frame building under the sudden column removal was investigated with a 3-D finite element model using ABAQUS package. Base on this model, parametric studies were carried out to investigate the structural behavior with variations in: strength of concrete, strength of structural steel, reinforcement mesh size, number of columns removal. Through the parametric study, the measures to mitigate progressive collapse design were recommended.

Below are main findings:

1. The typical multi-storey building with the cross bracing lateral resistance system used in the current design practice is less vulnerable to progressive collapse under the one column removal scenario. As long as the structural is designed with current BS ultimate state load combination, the structure should be robust enough to resist progressive collapse.

2. The effective way to mitigate the progressive collapse is to increase the strength of the steel structural members and the rigidity of beam to column connections.

3. For this type of buildings, the tying force are mainly provided by the steel connection and steel members, the composite slabs plays an less importance role as most of the force is resisted by the structural steel members.

4. Although the steel mesh can provide more ductility for the joints, however, for the four conventional sizes (A142, A193, A252 and A393) used in the current composite design practice, the difference mesh size have slight influence on the behaviour of the structure.

5. Effective way to resist progressive collapse is to decrease the spacing of the grid or provide more redundancy in the structural scheme.

Further work of the author will be concentrated on more parametric studies to exam detailed structural behaviour of the building when structural steel members are in the plastic stage, therefore two columns removal scenario will be studied in detail in the consecutive research paper. At the meantime, the effect of the connection stiffness will also be examined in detail in the future research.

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