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Progressive Collapse of Reinforced Concrete Frame Structure under Column Damage Consideration

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Abstract

The research work is focused on progressive collapse analysis of reinforced concrete framed structure under column damage consideration using commercial software SAP2000. Nine story frame is selected and designed under gravity loads as per Pakistan Building Code. The frame is analyzed for progressive collapse under three damage cases; corner column damage, edge column damage and internal column damage. The frame is subjected to loading as described by General Services Administration (GSA) guideline for carrying out linear static analysis. The results include the variation of bending moment of beams and evaluation of demand capacity ratios(DCR) in the beams of the longer direction. The vertical deflections of the damaged joint are determined in cases with 0%, 40%, 60%, 80% and full damaged consideration. According to the GSA guideline atypical frame building having DCR values greater than 1.5 indicate more damage potential in the structural members. It is concluded that the edge column case with long bays is found critical because the bays with longer span have more damage as compared with smaller span bays. It can lead collapse of the frame in short interval of time and there is more possibility of loss of lives under such condition of structures. Based on this research it is suggested that the practicing engineer should incorporate the GSA guidelines for loading along with the other loads so that progressive collapse potential may be reduced up to some extent.

Key Words: Progressive Collapse; General Services Administration (GSA) guideline; Deflection; Demand capacity Ratio (DCR);

1. Introduction

The term ‘progressive collapse’ can be simply defined as the ultimate failure or large failure of a portion of a structure due to the spread of local failure from element to element throughout the structure. The effect of damage to the prime load bearing element results in sudden change of the load path and geometry of the building. The progressive collapse of building is occurred when the one or more vertical load carrying members (typically columns) are damaged. Once a column is damaged due to some accidental loading like; fire, impact loading and blast loading, the building’s weight (gravity load) transfers to the neighboring columns in the structure. It is a process in which elements of the structural system which is taken the desired gravity load distributes the gravity load to prevent the loss of critical element like column. In US, the General Services Administration (GSA) [1] and Department of Defense (DOD) provide a comprehensive guidelines and procedures for progressive collapse. The GSA criterion contains the threat independent approach for the progressive collapse. Progressive collapse analysis is important for building structures to provide a cost effective and safe design against progressive collapse. Due to progressive collapse resulting from blast or any other external action, a number of security offices, commercial centers, governmental structures, embassies, and industrial facilities are not secure and safe. It is very difficult to provide safety measures for the existing buildings but an effort can be made to make future buildings relatively safe and secure from progressive collapse. After 2001 world trade center attacks terrorist activities has been increased all over the world especially Pakistan. Loss of lives has resulted in monetary and economic damages due to progressive collapse of the buildings.

2. Related Literature

The literature available on progressive collapse mechanism is not sufficient but in developed countries a lot of research has been done which mainly focused on composite buildings. In Pakistan, all the multistory high rise building structures have made using concrete because economy of construction and the non-availability of structural steel is the main factor. After 2001 world trade center attacks a lot of research has been carried out which is as under:

B.M. Luccioni et al. (2003) [2] noted that due to different abnormal loadings in the recent years have become a great attention. The construction and design of buildings enables life safety in case of explosion have become the design concern for the structural engineers for many years. For urban areas, the uncontrolled traffic fetches the terrorist activities near or within the surrounding of the building. Protection against the external action like blast has the important goal for the structures having damage in the nearby area of the explosion. Computer simulation is the best technique for the progressive collapse.

A bomb attack on a luxurious hotel (Pearl Continental Hotel) located at Khyber road Peshawar is one of those buildings that experienced progressive collapse as shown in figure 1. The columns of the ground floor were fully damaged by the impact of blast. The building stability was disturbed after the blast. A cantilever portion develops at third floor level of the building. While capacity to form alternate paths is present in the building, large overturning moment formed by cantilever portion results in collapse of the building.

Fig. 1 Progressive collapse of Pearl Continental Hotel Peshawar

Marjanishvili (2004)[3]evaluated that progressive collapse is a dynamic event in which building element shows vibrations which results in dynamic feature of inertial force. In a general manner he discussed analysis for estimating the progressive collapse behavior of the structures such as linear and nonlinear static and linear and nonlinear dynamic analysis. The nonlinear dynamic analysis shows the most realistic output, but due to high complexity of this, it is giving incorrect assumptions and modeling errors.

A research study was conducted by Sezen and Song (2008)[4] to test the progressive collapse potential of the Ohio State Union scheduled for demolition in 2007. They followed the GSA (2003) guidelines and calculated the DCR values as four exterior columns were removed from the structure. The computer program SAP2000 was used in the study to generate a computer model simulation of the Ohio State Union.

Hayes et al. (2005) [5] developed an idea of strengthening the structure against earthquake and to perform an analysis case of the building in the Oklahoma City bombing event. Updated Current code is used for detailing and three different strengthening schemes were used. Strengthening the perimeter elements increased progressive collapse potential while internal strengthening elements was much less effective.

Giriunas (2009)[6] completed a study involving the comparison of results from field testing of a real building to that of a computer model developed using the computer program SAP2000. The data from the field was analyzed and compared with the data from SAP2000 software [7].

Abruzzo et al. (2006) [8] performed a study describing the assessment of an existing building. It shows through usage of the alternate path method, the building meets the ACI 318 (2008) integrity requirements; it is still significantly vulnerable to progressive collapse failure. This study is also closely related to this project and should be useful in analyzing real buildings.

Abhay A. Kulkarni, Rajendra R. Joshi (2011)[9] performed an analytical modeling of 12 story building using ETAB v9.6 and SAP2000. The demand capacity ratios(DCR) of 12 story framed structure are assessed as per GSA guidelines. Linear and nonlinear static analysis is performed for comparison purpose.

3. GSA limit for Acceptance:

The GSA describes the use of the DCR (Demand- Capacity Ratio), the ratio of the member force and the member strength, as a reference to define the failure of main or important structural members by the linear analysis method.

$$DCR = \frac{DEMAND}{CAPACITY} \quad (1)$$

Where,

- *Demand* equals the moment demand calculated using bending moment diagram in linear static analysis.
- *Capacity* equals the nominal moment capacity.

The allowable limit of DCR values for primary and secondary structural elements are:

- DCR< 2.0 (Typical structural configurations)
- DCR< 1.5 (A-typical structural configurations)

4. Building Description

A nine story reinforced concrete building frame was selected for performing progressive collapse analysis. This reinforced concrete frame was a real building with slight modification to simplify the analysis and design process. The building has six spans in longer direction and three spans in shorter direction. The story height is 3.3m. The building plan is showing with dimension is given in figure 2. The beam sizes are (457mm x406mm), (457mm x457mm) and (635mm x457mm) and column sizes are (457mm x406mm) and (533mm x 533mm) are considered for the building. The walls having 115mm thickness is present on all the beams. The characteristics compressive strength of concrete (f_c') is 27.4 N/mm^{2}and yield strength of steel (f_y) is 413.6 N/mm^2.

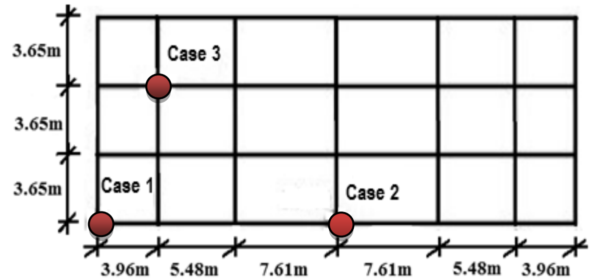

Fig. 2 The plan of the building

The longitudinal direction is considered as front elevation and shorter direction is considered as side elevation and it is shown in figure 3.

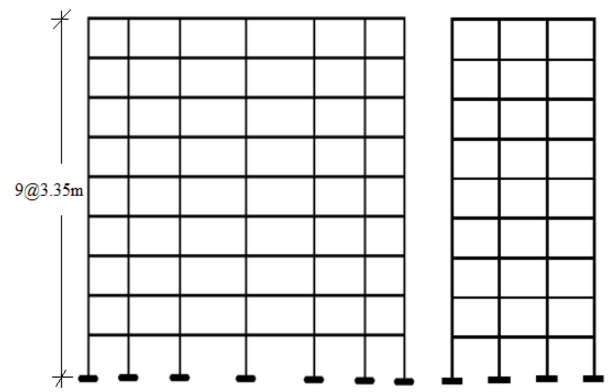

Fig. 3 Front and side elevation of building

5. Analysis Aspects

In the linear static analysis column is considered with damage from the location given in GSA guideline. The building analysis is carried out according to the load combination of this guideline. The gravity load $\{2(Dead\ Load + 0.25\ Live\ Load)\}$ is imposed on the frame structure. The slab was modeled according to the SAP2000 provision with refined meshing. The slab has thickness equal to 152.4 mm. The slab was taken as a shell element. The dead load and live load applied on the slab is 1.91KN/m^2 and 2.394KN/m^{2}respectively. The corner and internal column have same reinforcement which is 14#8 bars and edge column has 12#8 bars. The demand to capacity ratios(DCR) were calculated to assess the state of the building with damaged column. Check for the demand capacity ratio (DCR) in each structural member is carried out. If the DCR value of a member exceeds the criteria for acceptance, the member is considered as failed. The DCR values calculated from linear elastic method helps to define the possible potential for progressive collapse of frame structure. In case 1, column is considered with damage at the corner and its DCR values are shown in figure 4. The DCR values which are greater than 1.5 are represented in dotted form.

According to the GSA guideline atypical frame building having DCR values greater than 1.5 indicate that the portion is severely damaged and have more damage potential. It can be seen on the figure 4 that the demand to capacity ratio (DCR) values exceeds the acceptance criteria in above and adjacent part of the frame which shows collapse condition. But in other spans damage could not propagate. The maximum DCR value experienced by the frame is 6.7. In the event of blast or any external action, the corner column is very critical and the minimum requirement is that it should not collapse in this type of event. It can be observed that such damaged condition represent actual threat possibility and it is a technique of providing redundancy and continuity of the frame as well as deformation and load carrying capacity of the structural members. This damage consideration allows the designer to make the building strong and prevent them from progressive collapse.

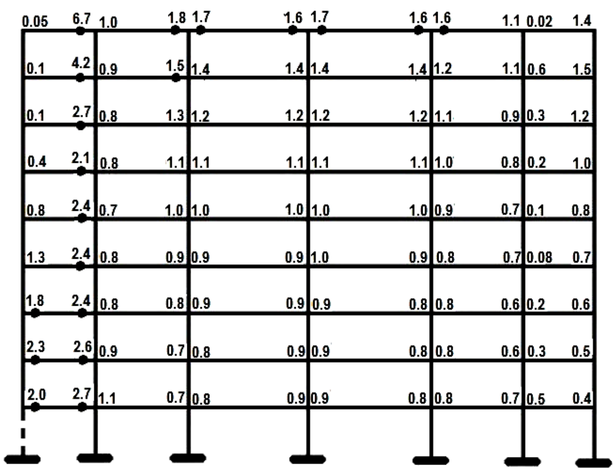

Fig. 4 DCR values of the corner column fully damaged case

The related researches indicate that columns are designed with more strength and in the direct design methods, resistance against progressive collapse is provided by enhancing the strength of key structural elements to resist failure under abnormal loads. Tsai and Huang[10] and Tsai and Lin [11] said shear failure was not considered and columns were assumed to remain elastic even after considering local damage. Dennis M. McCann and Steven J. Smith [12] said that balanced design often leads to a "Strong Column Weak Beam" approach, with the intent that beam failure is preferable to column failure.

In case 2, an edge column is considered as fully damaged column. Edge column is also critical and vulnerable in case of any external action such as blast or fire due of its position. As shown in figure 5, when column is considered fully damaged it is noticed that large increase in positive bending moment occurs at damaged place and above that because there is no support underneath. The cause of this rise is that in this bay large span beams were sustained by the column which was considered affected. The heavy loads on those members indicate increase in moment. The damaged column joint and the joints above that experienced stress reversal and there is also redistribution of moment above this part of the frame.

The DCR values of edge column case are given in figure 6.The DCR values which are greater the 1.5 are represented in dotted form.

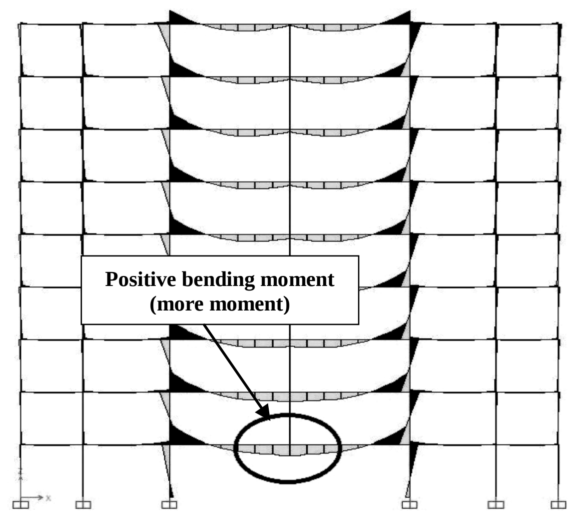

Fig. 5 Bending Moment diagram of edge column damaged case

When edge column is considered as fully damaged column, it is noticed that longer span bays show more damage than smaller span bays. The DCR values are greater than 1.5in the affected panel and damage is exceeded the acceptance criteria. The maximum DCR value experienced by the structure is

3.1.The DCR values are very consistent in this frame. This indicates that the building can fall in short interval of time and there is more possibility of loss of lives under such condition of structures.

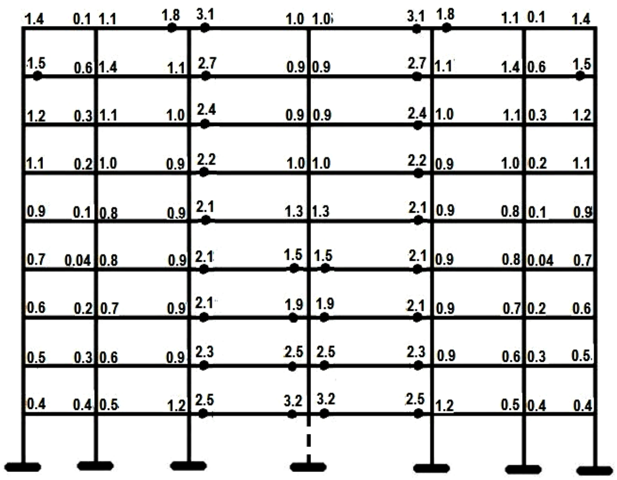

Fig. 6 DCR values of the edge column fully damaged case

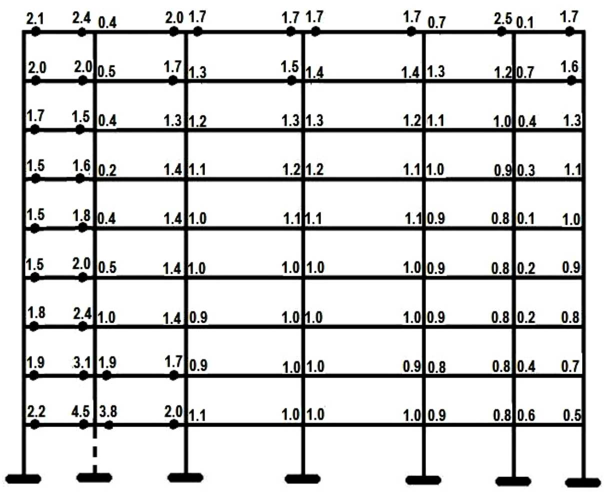

Fig. 7 DCR values of internal column fully damaged case

The Figure 7 shows the DCR values at front elevation of damaged column from the internal part of the frame. It is observed that the maximum DCR value is 4.5is present near the affected column which is very high. The beams adjacent to the column damaged joint experience more damage. The top floor beams or the upper portion of the frame have DCR values greater than 1.5 exceeds the acceptance criteria. The most of the beams away from the column damage joint are in the allowable range.

The figure 8 shows the bar chart for corner, edge and internal column damaged cases in which column is considered for various level of damages i.e. 0% damage, 40% damage, 60% damage, 80% damage and fully damaged case. The values in this bar chart are drawn considering vertical deflection verses damages level. As it is noticed that when the column is not damaged the deflection values of corner, edge and internal column cases are 1.7mm, 3.3mm and 3.8mm respectively. Then there is gradual increase of the deflection values in 40% damage case and the values are 2.7mm, 5.1mm and 5.5mm respectively. In 60% damaged case there is further increase of the deflection values which are 3.7mm, 7.1mm and 7.1mm respectively. In 80% damage case there is also increase in deflection values which are 6.1mm, 11.5mm and 9.8mm respectively. Then there is abrupt increase in the deflection values and these are 16.3mm, 30.6mm and 16.1mm respectively.

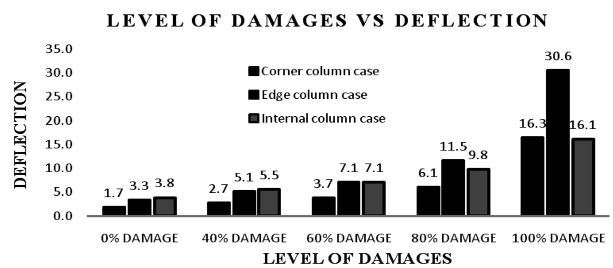

Fig. 8 Bar chart of level of damages vs. deflection

6. Conclusions

The conclusion drawn from progressive collapse of reinforced concrete frame structure under column damage consideration is as follows:

1. The selected reinforced concrete frame has high potential for progressive collapse when column is considered as fully damage.
2. The beams adjacent to the damaged column joint experienced more damage as compared to the beams which are away from the damaged column joint.
3. Edge column case having longer span bays found critical in the event of progressive collapse.
4. Longer span bays have shown more damage than smaller span bays. This indicates that the

building can fall in short interval of time and there is more possibility of loss of lives occurs in such buildings.

5. Due to different bays sizes, the demand has exceeded the available capacities.

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