3-D Nonlinear Static Progressive Collapse Analysis of Multi-story Steel Braced Buildings

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SUMMARY:

Progressive collapse is a catastrophic structural phenomenon that can occur because of human-made and natural hazards. The research on progressive collapse generally focuses on gravity and blast loading. Observations of buildings damaged by earthquake have shown that earthquake load also may cause local partial or complete failure of critical elements and may lead to progressive failure.
This paper presents the three and two dimensional modeling and push-over analysis of seismically designed special dual system steel frame buildings with concentrically braced frames with complete lose of critical elements. The study is conducted on multi story buildings by applying alternate load path method. The results show that parameters such as number of bays, height and location of eliminated elements have great influence on progressive collapse potential of buildings under seismic loading.

Keywords: Progressive collapse; push-over analysis; Concentrically braced frame; Alternate load path

1. INTRODUCTION

The term progressive collapse is typically used to refer the spread of an initial local failure within a structure. The local failure is triggered by the loss of one or more load carring members and lead to partial or total collapse of the structure. Following the initial event, the structure seeks alternative load paths to transfer the load originally carried by the damaged portions to the adjacent undamaged members. Since the later may or may not have adequate resistance to withstand the additional loads, further failures of overloaded structural elements are likely to occur, which in turn will cause more redistribution of loads until an equilibrium state is reached. However due to magnitude of the loads involved, equilibrium may only be achieved when a substantial part of the structure has already collapsed. Therefore, the main feature of progressive collapse is that the final damage state is disproportionately greater than the local damaged that initiated the collapse.

A progressive collapse can be triggered by a variety of causes, including design and construction errors as well as loading events that are beyond the standard design and are seldom considered by structural engineer. Such extreme events are typically associated with abnormal loads, e.g. gas explosion, bomb detonations and vehicular collision.

The remarkable partial collapse of the Ronan point apartment tower in 1968 initiated an intellectual discussion among the engineering community on the possible ways to design buildings against such catastrophic types of failure. While there have been several notable building collapses with similar characteristics in the years since Ronan point, the discussion considerably intensified after Word Trade Center disaster on 11 September 2001. In the aftermath of these events, several normalization comities started to rethink and improve their standards pertaining to progressive collapse design procedures. These include, for instance, the United States Department of Defense (DOD) or UFC, and United States General Services Administration (GSA), and Euro codes.

The two general approaches currently employed for mitigating the risk of progressive collapse include direct design method and indirect design method. The first is prescriptive approach of providing minimum level of connectivity between various structural components and therefore it can be readily implemented in structural design without the need for any additional analysis. On the other hand, the direct methods rely heavily on structural analysis that are commonly referred to as Alternate load Path Method (APM) and Specific Local Resistance Method (SLRM). In the direct design method, the potential for progressive collapse is reduced by either designing the structure so that it can bridge across the local failure zone or enhancing the strength of key structural elements to resist failure under postulated extreme load. In APM the structure is required to redistribute the loads after the loss of a primary load bearing member and remain stable. The present work focuses on this approach.

A number of structural analysis methods can be used to determine the resistance of the building to progressive collapse. Generally there are four type of analysis methodology, ranging from linear static to nonlinear static analysis and linear dynamic to nonlinear dynamic analysis.

Hartato Wibowo showed that progressive collapse phenomena can occur during earthquake; and also focused on the significance of seismic load effect in progressive collapse behavior of structures. It is concluded that seismic progressive collapse of structures can be analyzed by modifying the current analysis procedures. Kapil Khadelwal and Sherif El-Tawill investigated the progressive collapse resistance of seismically designed braced frames, namely special concentrically brace frames and eccentrically braced frames. The simulation results show that EBF system is less vulnerable to progressive collapse than SCBF system. Jinkoo Kim and Tawan Kim investigated nonlinear dynamic and linear static procedures using two-dimensional frame analysis. They found that steel moment frames designed for lateral loads as well as gravity load are less vulnerable for progressive collapse. It was observed that the potential for progressive collapse was highest when a corner column was removed and the progressive collapse potential decreased as the number of story increased. Min Liu used structural optimization techniques for design of seismic steel moment frames with enhanced resistance to progressive collapse. The potential of progressive collapse assessed using alternate path method as provide in UFC. The 2-D numerical example showed that linear static procedure has the most conservative result. In contrast, nonlinear static and dynamic procedure lead to more economical design.

The research of progressive collapse in structures generally focuses on gravity and blast loading. Nevertheless, earthquake load may also cause progressive collapse because of partial or complete failure of critical element as a result of vehicle impact or past earthquake shock, or design and construction error.

Dual systems such as special moment resisting frames with concentrically braces are popular structural systems that are commonly used in region of moderate to high seismic risk. In this system, the steel braces provide major part of lateral strength and stiffness to the structural system and contribute to seismic energy dissipation by yielding in tension and bucking inelastically in compression. The seismic performance of this system is fairly well understood. However their progressive collapse behavior under seismic load when critical members are lost, is yet to be investigated and is the focus of this paper.

Unified Facilities Criteria (UFC) and GSA guidelines employ the alternate load path method to ensure that structural system have adequate resistance to progressive collapse under abnormal or blast loading, Nonetheless we used this method for seismic loading. Naturally, all procedures are based on several levels of idealization, but the absence of computational methodology in standards and the lack of validation in others, thus justify the need for a research program focusing on alternate load path analysis for structure under earthquake load. By using two and three dimensional push-over analysis on this system it would be checked if a building can successfully absorb loss of a critical column, or no.

Irrespective of selected level of structural idealization three main assessment stages are considered namely, capacity curve comparison, robustness index determination and plastic hinges rotations. Two main scenario are considered, including removal of middle column and adjacent braces and the other, removal of corner column. The results varied more significantly depending on the variables such as number of spans, location of column removal and number of building stories.

2. ANALYSIS PROCEDURE

2.1 Acceptance Criteria and Analysis Method under Lateral Loading

For the nonlinear analysis procedures, UFC and GSA guidelines specify maximum plastic hinge rotation as acceptance criteria for progressive collapse. Table1 shows these acceptance criteria recommended in UFC 2009 and GSA2003.

Table 1. Progressive collapse acceptance criteria

Component	Performance level UFC2009	Rotation (radian) GSA2003
Steel beams	CP	0.21
Steel columns	LS	0.21

In UFC guideline indicated that progressive collapse assessment of the structures must carried out by three dimensional models. The 3-D simulations can include three dimensional effects for the flexural behavior of the members. The push over terminology is very common in seismic design, where practitioners often use such quasi-static equivalent analyses. The nonlinear static analysis (NSP) shall be permitted for structures in which higher mode effects are not significant. The NSP is generally a reliable approach to characterizing the performance of structure. So, for nonlinear static analysis for progressive collapse under seismic loading, three dimensional model of multi story special dual system steel structures with moment resisting frames and X braces was considered and two dimensional ones for comparison was used.

Model structures are designed per Iranian building code and the results of push-over analysis in target displacement were compared with UFC and GSA acceptance criteria for nonlinear analysis.

2.2 Lateral Load Patterns and Gravity Loads

Lateral load redistribution applied on model structures must similar to imposed earthquake load and produce critical deformation and damage mode in members. According to FEMA356 at least two type of load distribution pattern must be used and use in positive and negative directions. In present work these pattern are selected as follows:
a). Triangular pattern which is proportioned with lateral loading distribution in structure height according to equivalent static method
b). Uniform pattern in which lateral load is distributed proportionally with each story weight.

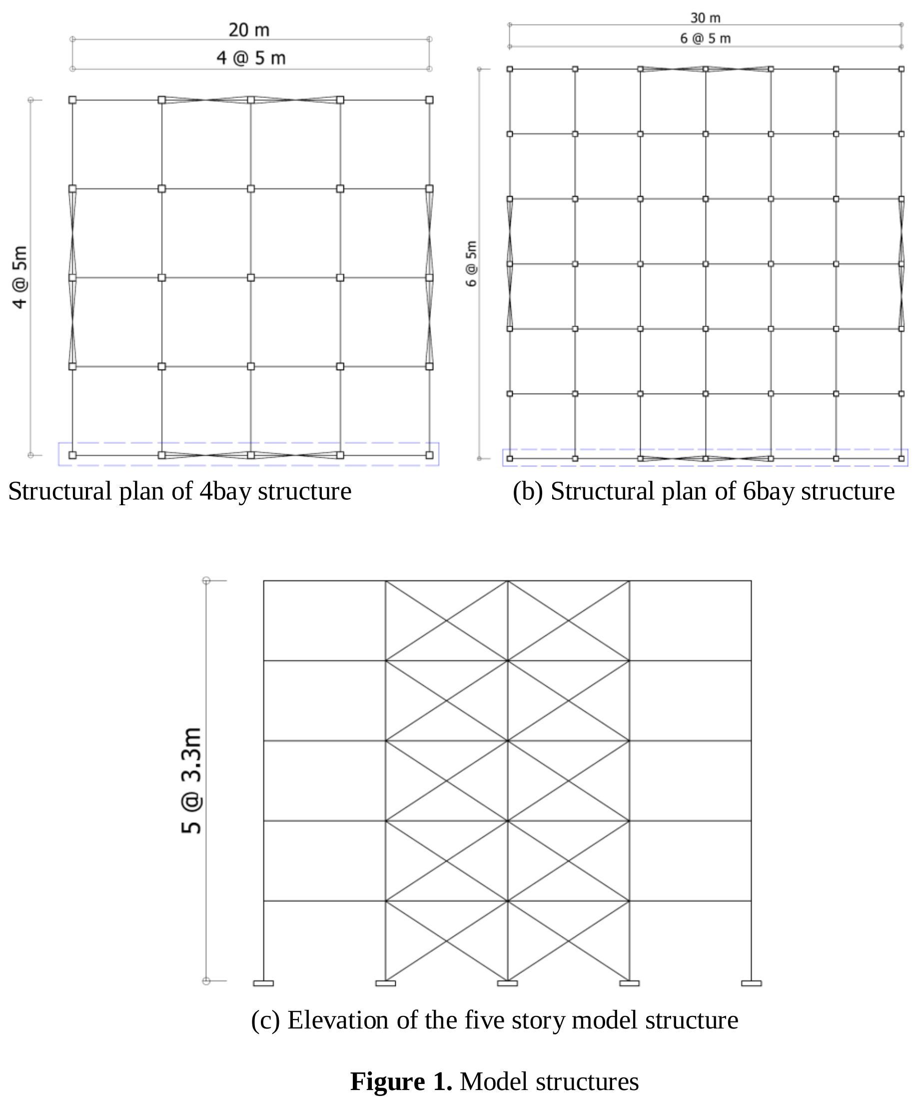
The gravity load on the members is a combination of dead load (DL) and live load (LL). The load combination was assumed to be DL+0.25LL, that is in a good compatibility with GSA2003 guideline for progressive collapse analysis and proposed load combination for push-over analysis for seismic analysis. In gravitational progressive collapse analysis, when using nonlinear static procedure, amplification dynamic factor applies on the above load combination, but in this study, it is assumed that vertical element has lost its load carrying rule as a result of past event and lateral load imposed on the other time, so dynamic effect of element removal is neglected and no dynamic factor is used.

2.3 Analytic Models

In this paper structural response is modeled using macro models. Macro models are fairly simple to build and run, and as much, they have been successfully used in past by many researchers to investigate system response to seismic loading. Structural models are able to account for buckling and post-buckling behavior of braces. The buildings are designed to resist both gravity and lateral loads in accordance with Iranian code and passed all seismic criterion containing strength and drift limits.

Structures is considered to be in high seismic zone and designed as special dual system steel moment frames with concentrically X braces. The columns and girders were designed with F_y=240 Mpa. For numerical analysis two and three dimensional structures using PERFORM 3D software were modeled, and for the material behavior elastic-perfectly plastic model was used. Despite of the GSA and UFC document prescribing limitation on shear effort, resistance criteria relative to this are neglected. This implies that only the ability to take in to account stress redistribution for bending efforts is investigated.

5 and 15 stories buildings with 4 and 6 spans were prepared to assess progressive collapse as shown in Fig1. The effect of irregularity by transferring braced frame in plan was also investigated and results will be compared.



(a) Structural plan of 4bay structure (b) Structural plan of 6bay structure

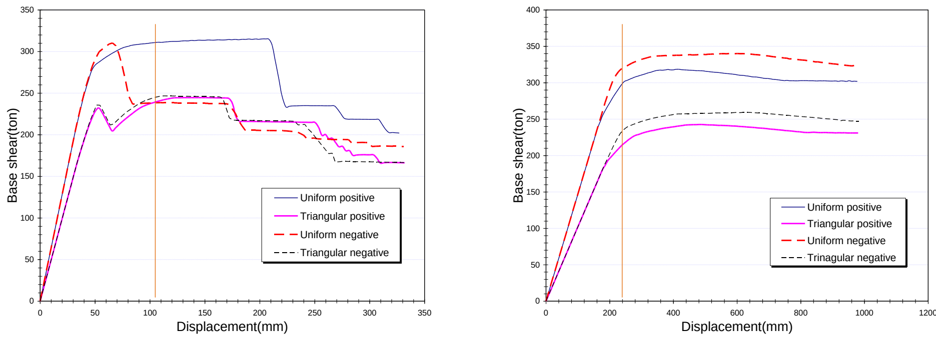
(c) Elevation of the five story model structure

Figure 1. Model structures

3. DISCUSSION AND RESULTS

3.1 Capacity Curves

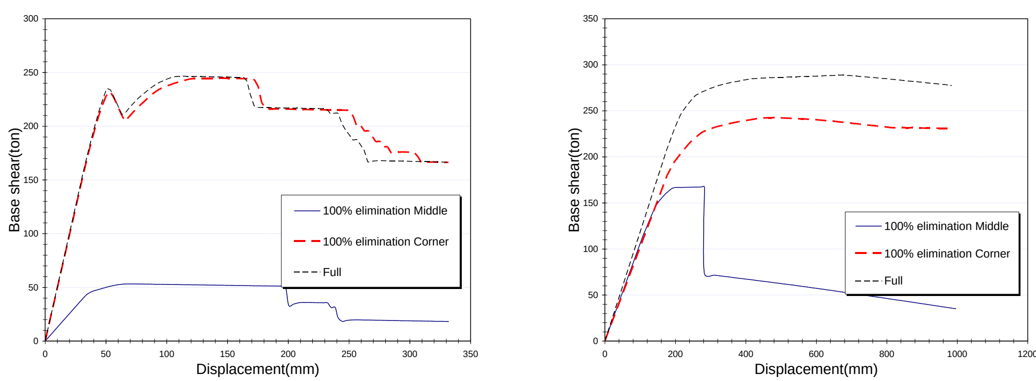
For the first step critical lateral load pattern that produce the least structural shear capacity and the worst damage mode is investigated. It is clear that various lateral load distributions are significantly different in capacity curves. For decreasing computational time, 2-D push over analysis on exterior frame of building was performed and difference of capacity curves in triangular and uniform patterns in positive and negative direction of load was assessed. Fig.2 is shown analysis result and the target displacement illustrated by vertical solid line.



(a) 5 story-4 bay -Corner column removed (b) 15 story-4bay-Corner column removed

Figure 2. Comparison of capacity curves in different lateral load pattern in two-dimensional structure

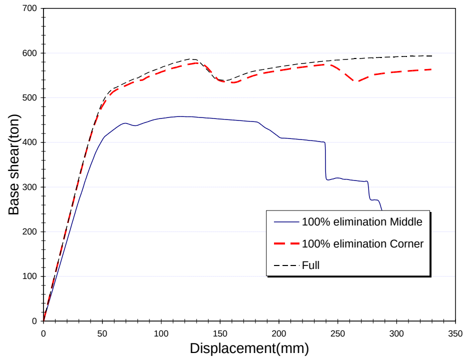
Investigation of capacity curves in studied frames showed that uniform load pattern produce a larger base shear capacity than triangular pattern. It is obvious that in the case of middle column removal, because of symmetrical conditions, load patterns in positive and negative direction generate a same shear capacity curve but when the corner column is removed positive and negative result is differed. As a result triangular pattern in positive direction shows the least base shear capacity. Now investigation in critical location of column removal based on two dimensional model structures with triangular pattern in positive direction is discussed in Figure 3.



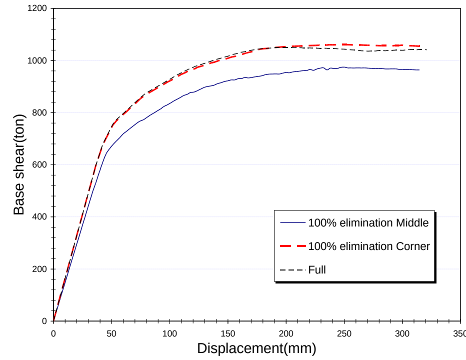
(a) 5 story-4 bay (b) 15 story-4bay

Figure 3. Comparison of capacity curve in different locations of column removal in two dimensional structures

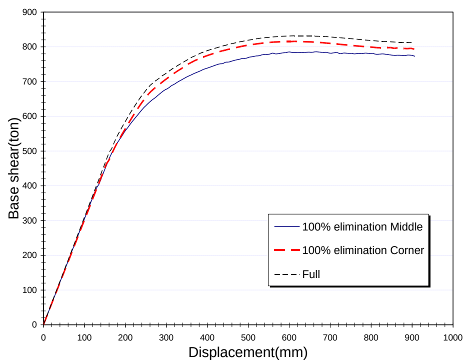
It is concluded that middle column and adjacent brace removal have more considerable effect on shear capacity of structures than elimination of corner column alone. This illustrated significance of braces in dual systems to absorb lateral forces and catastrophic result that may occur after the brace failure. 3-D push over analysis in triangular load pattern in positive direction was carried out and capacity curves in different models and position of element removal was compared. Fig.4 shows these curves in three dimensional regular models.



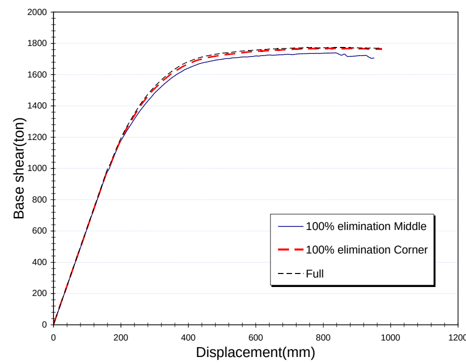
(a) 5 story-4 bay structure



(b) 5 story-6 bay structure



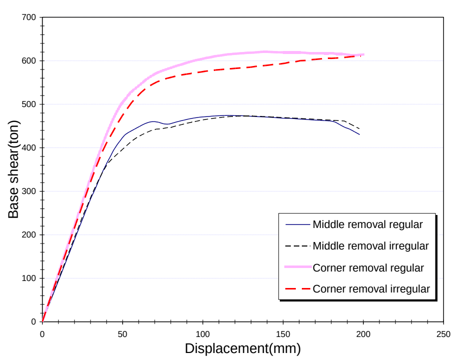
(c) 15 story-4 bay structure



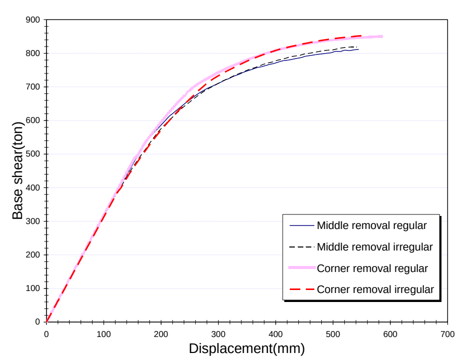
(d) 15 story-6 bay structure

Figure 4. Comparison of capacity curve in different locations of column removal in three dimensional structures

It can be seen that by increasing span's number and height of structure, difference between capacity curves is going to be shorter and the models show less sensitivity to element removal. So the numbers of stories and spans in the structures can have a considerable effect to resist progressive collapse in structures and create more redundant and robust structure. Because the numbers of participating members and load redistribution paths extremely increase with the more bays and stories numbers.Fig.5 illustrated irregularity effects on shear capacity of structures.



(a) 5 story-4 bay structure



(b) 15 story-4 bay structure

Figure 5. Comparison of capacity curve in different locations of column removal in three dimensional regular and irregular structures

Irregular models are created by one span displacing of peripheral braces perpendicular to lateral imposed load in 4 bay structures. As a consequence in the case of difference between center of mass and center of rigidity in the plan, structures show smaller shear capacity than regular models. What is sensible is that the difference between curves by raising the height, come to be less.

3.2. Robustness Indicator

Robustness is structural ability to survive the event of local failure. On the other word, robust structure has a reasonable insensitivity to local failure so it can withstand the loading with no disproportionate damage. In order to quantify the results, an indicator of robustness is defined. If the design load is equal for the intact and damaged structure, R can be written to:

$$R = \frac{V_{(damaged)}}{V_{(intact)}} \tag{3.1}$$

In Eqn.3.1 V is the base shear capacity and R is the residual reserve strength ratio. If the intact and damaged structures have same capacity the value is one, if the damaged structure has no capacity it is zero. For a lateral load the base shear capacities can be found by performing a static push over analysis.

Robustness index values with different lateral load distribution in 5 and 15 story with different location of column elimination calculated by two dimensional model was indicated in table 2 Study on these quantities show that in the case of middle column and brace removal the strength reduction is more than corner column removal scenario. It is also noticed that lateral load patterns has no significant effect on Robustness index and the result is almost the same.

Table2. Structural Robustness assessment for 2-D models

Story	Bay	Removed column	Robustness Uniform pattern	Robustness Triangular pattern
5	4	Middle	0.17	0.2
		Corner	0.98	0.93
15	4	Middle	0.51	0.49
		Corner	0.83	0.84

Fig.6 plotted comparison of two and three dimensional robustness index, when the middle column and brace are lost. Irregularity effect is also illustrated. It is noticed that two dimensional models are more affected by local failure than three dimensional structures and are more sensitive to base shear reduction as a result of element removal. Unfavorable effect of irregularity on robustness of structures is going to be negligible as the height of structures increase. For assessment of irregularity, triangular load pattern with 100% in X direction and 30% in Y direction was used.

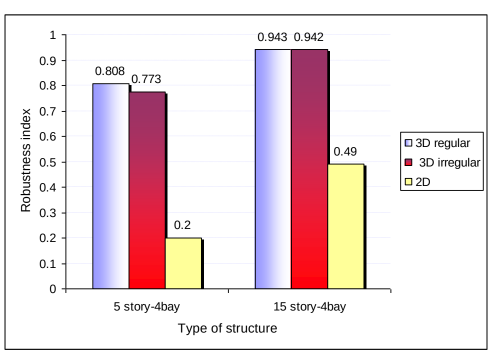


Figure 6. Comparison of robustness index in 2-D and 3-D models and irregularity effect under middle column and brace removal

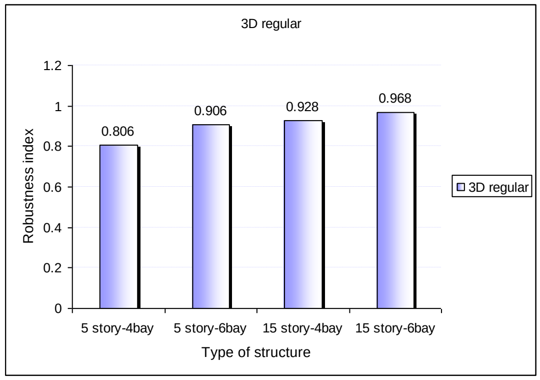


Figure 7. Comparison of robustness index in 3-D models under middle column and brace under triangular load pattern in positive direction

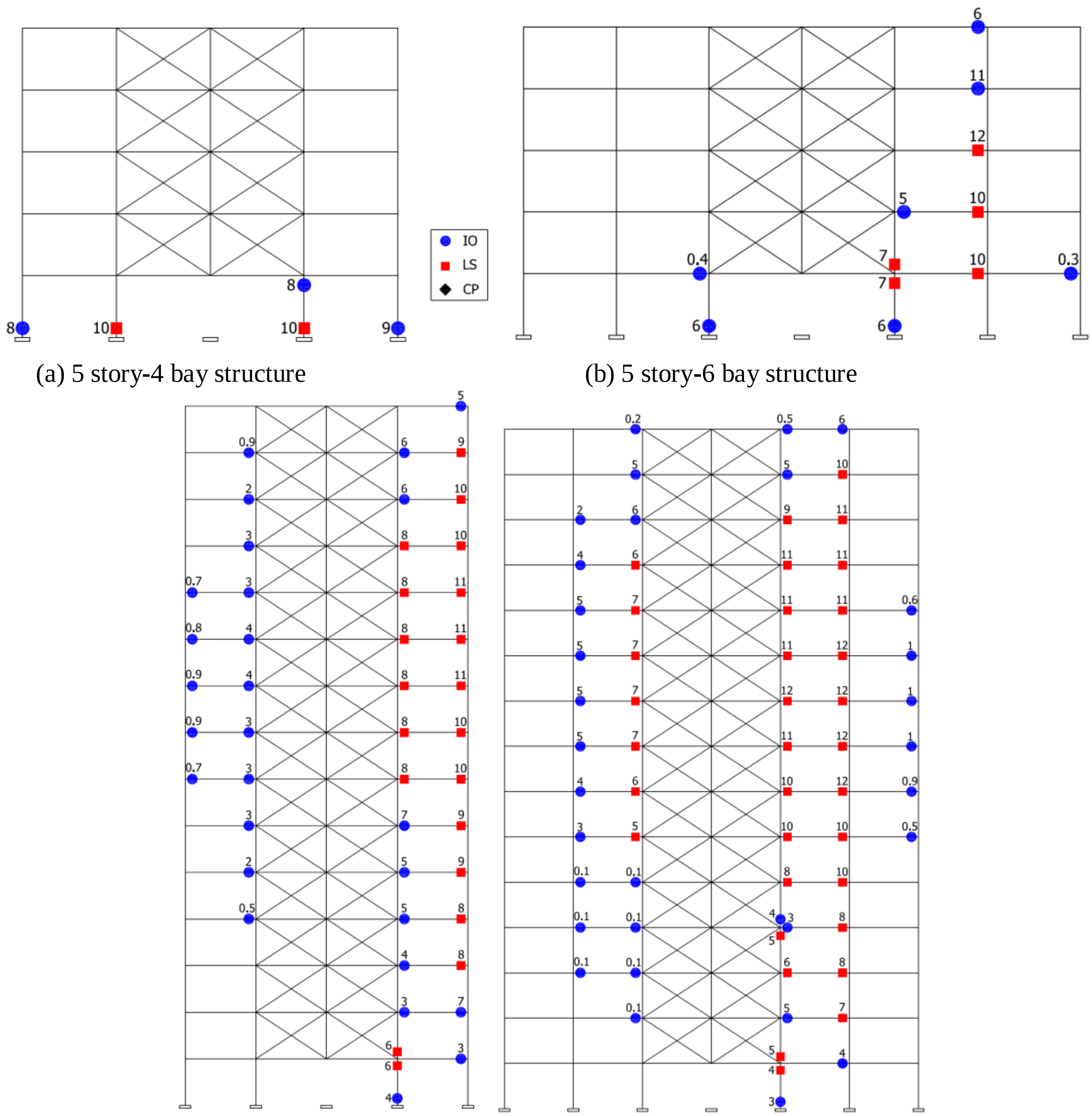
Fig.7 shows that increasing the number of bays and stories, induce higher level of robustness index. So for many cases, it is better to ensure the robustness by choosing a redundant structure. A redundant structure is characterized by being statically indeterminate. Therefore structure is able to provide alternate load path, if structure is damaged.

3.3 Plastic Hinge Rotation

Hinge rotation limitation is the most important part of guidelines that is available for progressive collapse assessment of structures. As mentioned later, UFC2009 guideline presented hinges rotations in collapse prevention (CP) performance level for the beams as a limit state. In GSA2003 this is limited to 0.21 radian. If the beams above the lost column, exceed these limits, the structures have a high potential of progressive collapse. Rotation of the hinges investigated in target displacement. The target displacement shall be calculated in accordance with FEMA356. Hinge rotations on target displacement in exterior frame of the model were compared with acceptance criteria for progressive collapse. Fig.8 shows the location of plastic hinges and their performance level and rotation, when middle column and braces removed.

The results show that the special dual systems with X brace in steel structures are capable to absorb element loss. The force levels in remaining beams, column and braces are small enough that they essentially response in an acceptable manner.

When the middle column was removed no plastic hinge rotation exceeded the given acceptance criterion. Therefore, there is no potential of progressive collapse in the middle column lose situation based on UFC2009 and GSA2003 guidelines. It is noticed that from the hinge formation in local damaged structures that safety margins for progressive collapse potential is sufficiently enough and there is no need to design structure with an extra requirements.



(a) 5 story-4 bay structure (b) 5 story-6 bay structure

(c) 15 story-4 bay structure (d) 15 story-6 bay structure

Figure 8. Formation of hinges when middle column and brace is completely removed under triangular positive load pattern (rotation in thousandth of radian)

4. CONCLUSIONS

Two and three dimensional model of a popular type of lateral loading resisting system, namely special steel moment frame with X braces were developed in this work. The studied structures consist of 5 and 15 floors with 4 and 6 bays. The main conclusions are obtained as follow:

• The buildings designed according to seismic specification, when a column and adjacent braces in the first story for any reason did not do their load carring role properly, were strengthen enough to resist progressive collapse and no plastic rotation exceeded given acceptance criterion. As the rotation of plastic hinges were relatively small compared to standards limitations, despite of having limited simulation, it is predicted that the system will not collapse progressively for these scenarios.

- Comparison of lateral loading pattern showed that triangular pattern induce the least capacity curve for intact and damage structure but the robustness index in uniform and triangular pattern is almost the same.
- When the number of stories and bays are increased, larger capacity to resist progressive collapse under lateral loading and higher level of robustness index obtained. Because additional elements were participated to resist progressive collapse. Unfavorable effects of Irregularity were going to be negligible as the same manner.

Nevertheless, it seems there is no concern about occurrence of progressive collapse under seismic loading in one column and adjacent brace lose scenario for steel special dual systems containing special moment resisting frame and X brace.

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