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Effects of Steel Bracings in the Progressive Collapse Resistance of Reinforced Concrete Building

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Abstract. The bracing system used in the seismic retrofitting can also be used as a measure to resist the progressive collapse of the multi-storeyed structures. The nonlinear dynamic analysis is used to study the effects of floor wise and bay wise bracing systems in the progressive collapse resistance of seismic designed reinforced concrete buildings. The numerical model is created in SAP2000 and is analysed for three different column removal scenarios using UFC guidelines. The results showed the significant contribution of the bracing system to prevent the progressive collapse due to single removed column. The bay wise bracing system is more effective to reduce the deformations but there is no contribution of the bracings when the column is removed from the non-adjacent bay. The floor wise bracing is more reliable than bay wise bracings.

1. Introduction

The propagation of the failure from the critical members to the other members in a progressive manner leading to failure of the large proportion or complete collapse of the structure is called progressive collapse [4]. The collapse of the twin tower by the terrorist attack of world trade center in 2011 has created a great interest in the study of progressive collapse and in the design of the robust structures which can stand safe and stable even when some of the member fails.

The steel bracings are the most common retrofitting measure in lateral load resisting system. It provides additional stiffness by transferring tensile or compressive forces in the alternating cycles of load. Similarly, it can provide additional robustness by forming a truss like bridge across the missing elements and help in stress redistribution to the larger number of elements. The bracings decrease the stress of the horizontal members and prevent the initiation of the progressive collapse chain.

The General Services Administration [1] and Unified Facilities Criteria 4-023-03 [2] are the most commonly used guidelines for the progressive collapse analysis. Both guidelines use alternate load path method and the analysis could be done using linear and nonlinear static and dynamic method. Many researchers have studied the effectiveness of bracing in progressive collapse resistance of steel moment frames [5-7]. Similarly, the most of the studies of progressive collapse of reinforced concrete shows the resistance is provided mainly due to compressive arch action, tensile catenary action or tensile membrane action [9]. There are only few studies showing the contribution of steel bracings in reinforced concrete buildings. Qian et al. [9] experimentally studied the one quarter model of 2 bays, 3 story sub-frame of seismically designed eight storied building with different bracing configurations. The experiment showed that the eccentric cross bracing have higher dynamic load capacity while V braces and reversed V braces configurations have mild effect in improving the load resisting capacity. However, the study of the global behaviour of the braced reinforced concrete building in resisting progressive collapse is limited.

This paper aims to study the capability of the seismically designed and retrofitted structures in resisting progressive collapse. The nonlinear dynamic analysis of the eight-story seismically designed steel braced reinforced concrete frame is carried out to show the contribution of braces.

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2. Analytical Model

Three dimensional reinforced concrete buildings are modelled and analysed by commercial finite element software SAP2000. The progressive collapse analyses of eight-story braced and unbraced buildings were carried out using nonlinear dynamic analysis prescribed by UFC guidelines [2]. The building was designed for the low seismic zone and the design parameters are shown in the table 1 and 2. Three types of column removal scenarios (a) corner column removal (b) Middle Column of shorter side and (c) Middle column of longer side are considered, one at a time as shown in the figure 1.

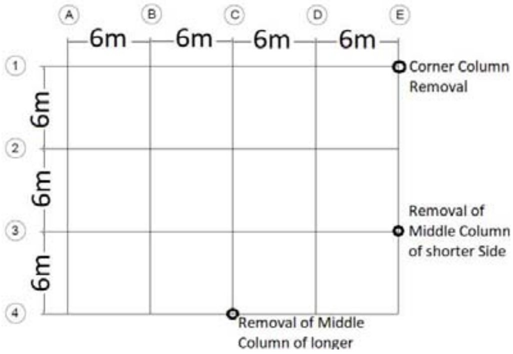


Figure 1. Plan and Column removal locations

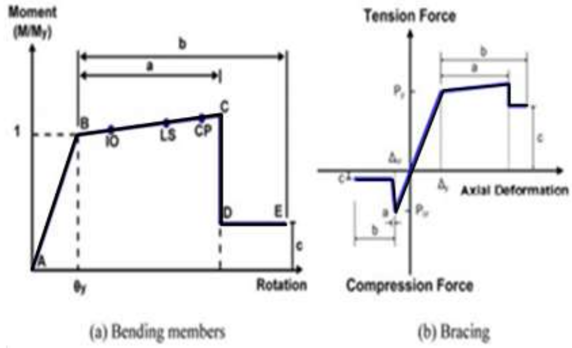


Figure 2. Hinge definitions for beams and bracings[11]

All the beams and columns are modelled by 2-noded beam elements with the beam column connection being moment resisting. The bracing members are added as pinned connection on both ends. The support condition at the foundation is modelled as fixed connection. The effect of membrane action of the reinforced concrete slab is not considered. The structure is designed as per the concept of strong column and weak beam. So, the column section remains elastic even after the load redistribution due to loss of column. Also, the plastic hinges are allowed to form in the beam body only. At large rotations, several cracks occur in the reinforced concrete beam section. This reduces the effective moment of inertia (I). So, the moment of inertia of the beams is taken as 0.3I as indicated in Table 10-5 of ASCE 41-13 [3].

Table 1 Design Parameters

Element	Size(mm)	Reinforcement
Beams	500 x 300	Top 3-16dia Bottom 3-12dia
Columns	500 x 500	8-16dia
Bracings (Tube)	HSS4-1/2x4-1/2x0.5 (inch)	Fe345 grade steel

Table 2 Structural Loadings

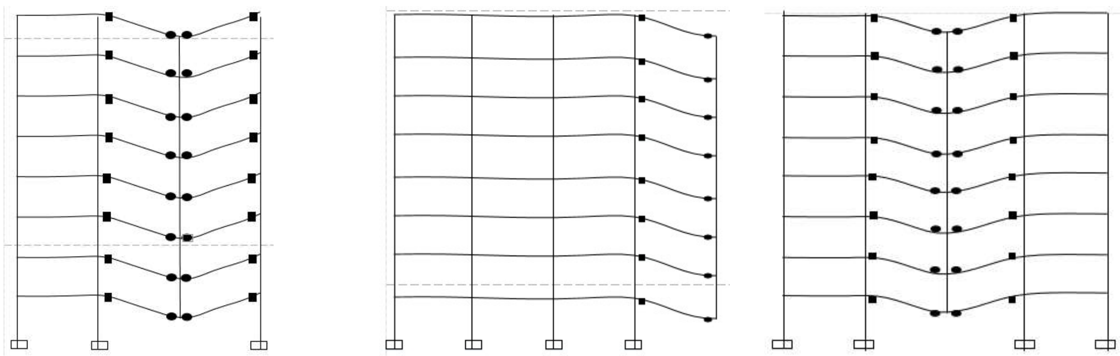
Live Load	3KN/m^2
Roof Live load	1.5KN/m^2
Wall load	10KN/m
Slab Load	3.125kN/m^2

Note: The dead loads of the modelled elements like beam, column and brace are taken automatically by SAP2000

The modulus of elasticity and compressive strength of concrete is taken as 25000 Mpa and 25 Mpa respectively. The yield strength of reinforcement is taken as 500 Mpa. The material non linearity is included in the model by defining the concentrated plastic hinges [3]. The nonlinear hinges of beam and braces are defined in the form of normalized force displacement curve (moment rotation curve for beam) as shown in the figure 2a and 2b. Points A, B, C, D and E represents the origin, yielding point, the ultimate capacity, residual strength and total failure (square shaped hinges shown in the figure) respectively. The points IO (Immediate Occupancy), LS (Life safety) and CP (Collapse Prevention) in line BC are the acceptance criteria and are considered acceptable by the UFC guidelines [2]. For the geometric nonlinearity, P-delta effects plus large displacements option available in SAP2000 is used [10]. In nonlinear dynamic collapse analysis, the simulation of sudden removal of column is done by replacing the column by its internal forces resulting from ASCE 7 load combination 1.2DL+0.5LL as reaction and then this reaction force is suddenly dropped to zero in 0.01 second by using the time history function in SAP2000.

3. Results

The dynamic analysis of the unbraced frames showed that the hinges of the beams in the affected spans, reach the failure point E (square shaped hinge) as shown in the figure 4 in all the cases of column removal scenario. So, the building designed for low seismic zones are vulnerable to progressive collapse. The failure of one column leads to the collapse of all the members in the affected span. Hence, steel bracings are used as the remedy to provide resistance against the progressive collapse. Two types of bracing systems considered are (1) Floor wise bracing and (2) Bay wise bracing as shown in the figure 5 and figure 6 respectively.



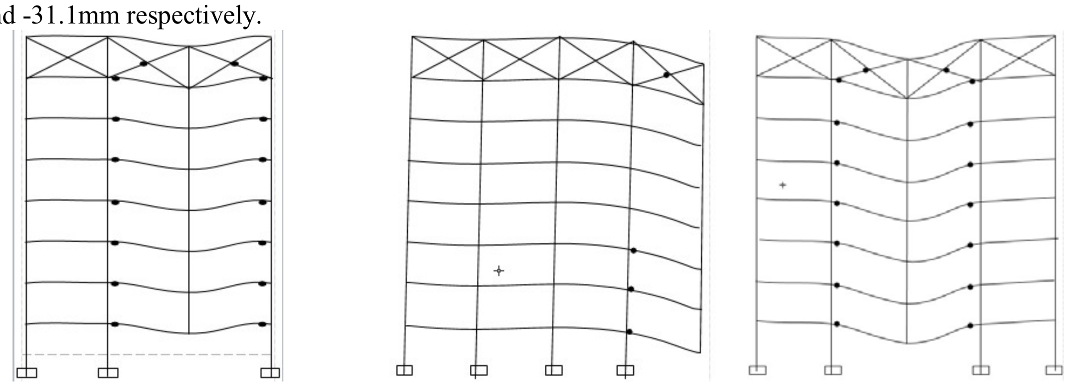
a) Middle Column of short side (b)Corner column removal c) Middle Column of long side

Figure 3. Deformed shape and Plastic Hinge states for Unbraced Frame

3.1. Floor wise bracing system

In all the cases of column removal scenario, the floor wise bracing system is capable to strengthen the building to resist the progressive collapse although few bracing members fail by buckling in compression. The plastic hinges formed in the beams are within the immediate occupancy (IO) range which meets the required acceptability limit defined by UFC guidelines.

The sudden removal of column creates the dynamic overload of the structure due to which the column removal point displaces downward to the peak displacements and then it oscillates and finally stabilizes to the fixed permanent deflection. The time histories of the displacements are shown by dotted line in figure 7(a), 7(b) and 7(c) for three cases of column removal. The peak displacements for corner column removal, middle column removal for shorter and longer side are -27.1mm, -32.2mm, and -31.1mm respectively.



a) Middle Column of short side (b)Corner column removal c) Middle Column long side

Figure 4. Deformed shape and plastic hinge state for the floor wise bracing system

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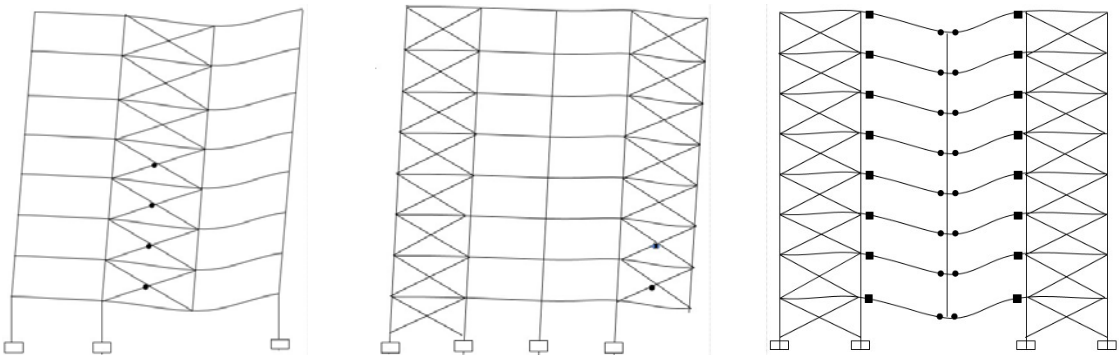
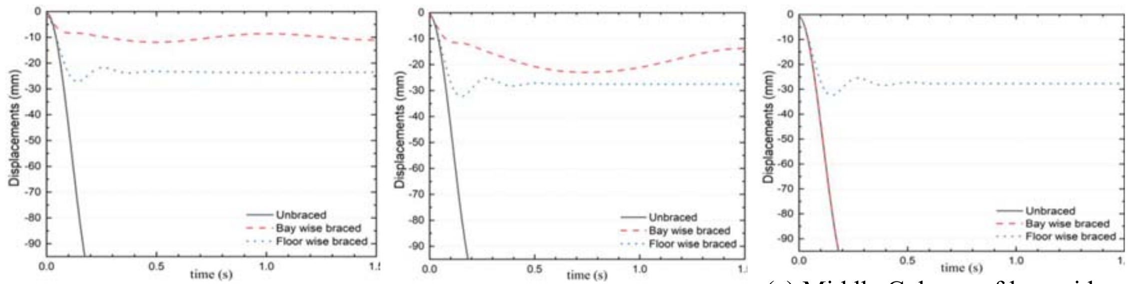
3.2 Bay wise bracing system

As shown in the figure 6(a) and 6(b), the bay wise bracings are capable of resisting the progressive collapse with the failure of few compression braces. The plastic hinges do not form in the beams and the displacements of the column removal point are relatively smaller than that of the floor wise bracing systems. The time histories of the displacements are shown by dashed line in figure 7(a), 7(b) and 7(c) for three cases of column removal. The peak displacements for corner column removal and middle column removal of shorter side are -11.8mm and -22.12mm respectively.



a) Middle Column of short side (b)Corner column removal c) Middle Column of long side

Figure 5. Deformed shape and plastic hinge state for the Bay wise bracing system



(a)Corner column removal (b) Middle Column of short side (c) Middle Column of long side

Figure 6. Comparison of time history for vertical displacement of column removal point

However, the removal of middle column of longer side shows the occurrence of progressive collapse as shown in figure 5(c)(square shaped hinges represent beam failure) because there is no bracing member near the removed column to provide the alternate path for the force redistribution.

4. Conclusion

a. The bracing systems are effective in reducing the deformations of the members significantly. So, the bracing system used for the seismic retrofitting can also help to prevent the progressive collapse.
b. The displacement is the least for the bay wise bracing configuration. But it is ineffective when the middle column of the longer side is removed.
c. The floor wise bracing reduce the deformations with lesser number bracing members. This type of bracing is more reliable because it has significant contribution in the progressive collapse resistance in all the cases of exterior and corner column removal. The deformations could be further reduced by adding such bracings to two or more floors (top and intermediate floors).

d. The number and severity of plastic hinges are greatly reduced when the bracings are included in the frame. So, the bracing system can be useful for the older building designs with insufficient seismic detailing.[9]

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