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Effect of Belt Truss Systems on the Enhancement of Progressive Collapse of Steel Buildings

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ABSTRACT

Robustness, structural integrity and prevention risk of progressive collapse (PC) are among main design objectives for structures. After the (PC) of many remarkable structures, the need for better designing techniques has motivated engineers to prevent similar incidents.

The main objective of this study is to investigate different structural systems to detect more practical and cost effective systems to enhance the (PC) resisting capacity. The study is extended to numerically investigate the effectiveness of these systems by analyzing a ten storey steel office building using alternative pass method discussed by UFC09 code. The study shows that one of the preferred practices to reduce the potentiality for (PC) is the use of belt trusses at the top of the building. The use of belt truss system holds the initial failure of the damaged elements and redistributes the loads supported by the failed elements with the least increase in the structure's weight.

Keywords: Progressive collapse, belt truss**,** Alternate Path Method, Finite element, Robustness

INTRODUCTION

The development and application of efficient structural systems for important structures should include a major factor that affects its design concept which is its sensitivity to progressive collapse. The progressive collapse (PC) is an initial local failure that spreads from element to element, eventually contributing to the collapse of an entire structure or a large part of it. This mainly happens as a result of unexpected occurrences such as, impact, blast or natural disasters, (DOD, 2009). Reducing the risk of PC and the need for safer and improved building performance has motivated engineers to develop new design approaches that may help in minimizing the risk of mass casualties. Several researchers and code agencies develop new guidelines for the structural design to enhance robustness of structures and their resistance to PC, among of them, (Ellingwood and Dusenberry, 2005; Kaewkulchai and Williamson, 2006; Lee et al., 2009; Tay et al., 2012). Department of Defense (DoD, 2009) and the General Services Administration (GSA, 2003) provide detailed guidelines regarding methodologies to resist progressive collapse of building structures. Both code employ different ways to achieve alternative load path, one of them mention, in UFC09, is

Alternate Path Method (APM).

An investigation study has been carried out to examine the most common design strategies for collapse-resistant buildings.

INVESTIGATED STRUCTURAL SYSTEMS

The study investigates some of the common structural systems for mid-rise steel buildings along with their related risk progressive collapse resistance capacity. Moreover, the study is extended to detect the optimal system to be adopted. Five different structural systems / design approaches are included in the study:

1- Simple Connection Model (SCM), (the entire structure is simply connected).
2- Corner Rigid Columns Model (CRCM), (the corner columns are rigidly connected to the adjacent beams).
3- Partial Rigid Columns Model (PRCM), (the structural system is made of one rigidly connected column and the next one is simply connected to the adjacent beams).
4- Moment Resisting Frame Model (MRFM), (the entire structural is rigidly connected)
5- Belt Truss Model (BTM), (belt truss is included on the top of the outer columns which are simply connected to the beams).

To investigate the different structural systems, a linear static analysis method of APM discussed by UFC09 code is used. The APM is well applicable to continues beams and moment resistant connection to enable the structure to bridge the located failure element. The previous structural systems will be investigated for two conditions; the first one when one of the perimeter middle columns is removed (column1), and next, when one of the corner columns is removed (Column2), as shown in Figure 1.

THE ANALYTICAL MODEL

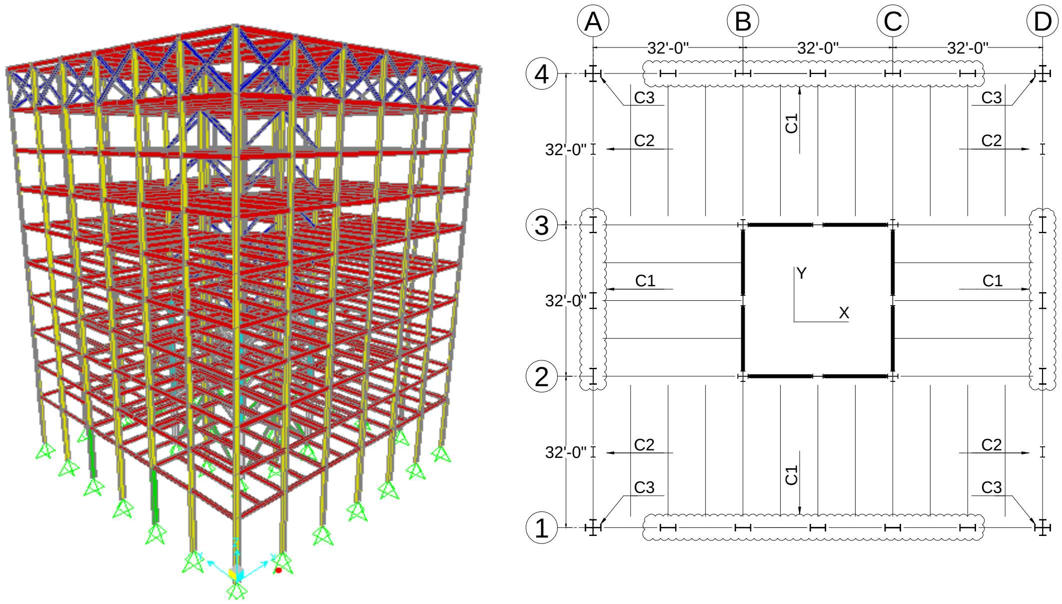
The analysis model is a ten storey office steel building with a plan dimension of 30m × 30m, as shown in Figure 1. The first floor height is 6m, and the typical floors height is 4m. The building is provided with internal braced core located at its center representing a lateral force resisting system. The vertical bracing shape is a K-braced diagonal element, while all gravity beams are joined with simple shear connections to columns. Structural steel members are wide-flange shapes comprised of ASTM A992 steel F_y = 345MPa (50 ksi). The floor system consists of steel beams and metal deck that will act together as a horizontal diaphragm to transfer all lateral loads to the vertical braced central core.

The cross section for of the beams along the Y-direction between axes (A to D) and along X-direction between axes (2 to 3) is W16X45. The cross section of beams along X-direction on axis (1 and 4) is W16X31 while beams on Y-direction between axis (1 and 2 & 3 and 4) are W16X26. The column cross sections are summarized in table 1.

Permanent load of each floor is estimated as 380 Kg/m^2, superimposed load 75 Kg/m^2, and self-weight of the steel elements is included automatically in the computer model. The live load is considered 487 Kg/m^2, as specified in ASCE 7-02, (2006) for office buildings. Wind and seismic loads are considered as specified in the UBC 97.

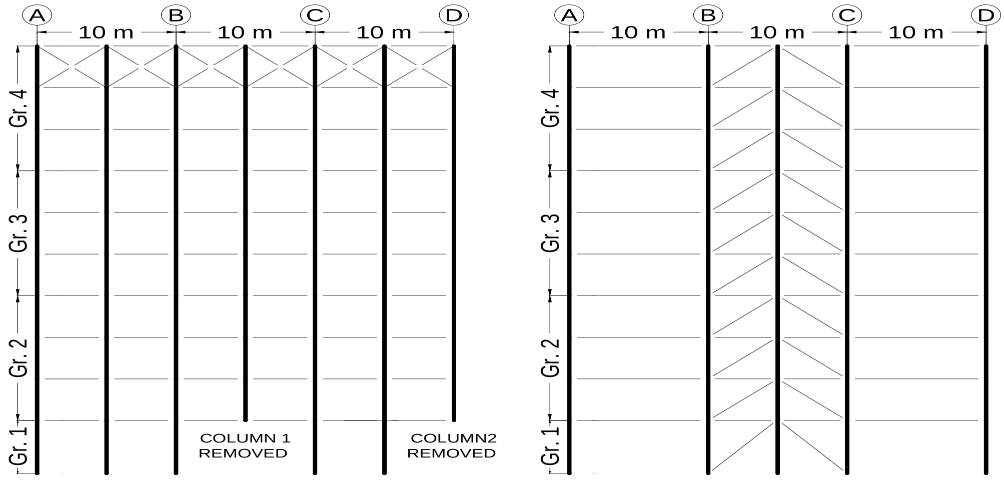
Table1. Columns’ cross-sections

Group	C1	C2	C3 (star shape)
Gr.4	W18X35	W18X50	2-W18X35
Gr.3	W18X40	W18X71	2-W18X35
Gr.2	W18X46	W18X76	2-W18X35
Gr.1	W18X76	W18X119	2-W18X35



a) Three dimensional model

b) Plan view



c) Exterior elevation at axes 1, 4, A& D

d) Interior elevations at axes 2, 3, B& C

Figure 1. Three dimensional model, plan view and elevations of the building (note: Five different structural systems / design approaches are considered for the connections: SCM, CRCM, PRCM, MRFM, and BTM)

METHOD OF ANALYSIS FOR PROGRESSIVE COLLAPSE

A 3-D finite element model is created using SAP2000 software package. The alternate path method (APM) approach recommended by UFC09 guideline is considered as an analysis and design method. Linear static analysis mentioned in UFC has special factors in combination to take the effect of material nonlinearity and the dynamic effect of PC event. UFC classified the acceptable criteria of the modeled structure elements to primary and secondary components according to its role play in resisting the progressive collapse.

Each structure element has different response according to its ductility. Component capacities permissible inelastic deformation limits shall be taken as deformation-controlled actions, and component capacities permissible elastic deformation limits (brittle failure) shall be taken as force-controlled actions. Then two models have been carried out to verify acceptability of components and actions which are deformation controlled and force controlled. The difference between the two modeling cases depends on material properties, load combination and acceptable criteria.

a) Load Combination. For floor areas that are immediately affected by a removed element, the following increased gravity loads are applied as per Equations (3-9) and (3-12) in UFC09;

$$G_{LS\_CL} = \Omega_{LS}\,[(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S)] \qquad (1)$$

Where, Ω_{LS} is the load increase factor needed to accounts for the dynamic and nonlinear effects following the sudden element removal. "Ω_{LS}" is equal to 2 for force-controlled load combination, while is equal to $(0.9m_{LIF} + 1.1)$ for deformation-controlled load combination. Where, m_{LIF} is the smallest value of m-factors of all primary structural components, excluding columns that are contributing to progressive collapse resistance and are within the immediately affected portion of the structure.

The m-factors are adopted from ASCE 41, and are indirect measures of the nonlinear deformation capacity of structural elements. Each component within the structure, elements and joints, is assigned an m-factor calculated from Table 5-5 in ASCE 41. For flexure members m-factors are determined as a function of member compactness, and for element stressed by axial and flexure action m-factors are determined as a function of both member compactness and axial compression force level. In addition, there are m-factors for different types of beam-to-column connections. In the present study, Table (5-1) in Chapter 5, mentioned in UFC09, the m-factor for beams subjected to tension force and connected with double angles is 1.5, and for welded unreinforced flange beams connected with bolted web connections, the m-factor is equal to (2.3 – 0.021d), where d is the depth of beam element (in inches). Then according to equation (1) and Table (5-1), Load increase factor is equal to 2.45 and 2 for deformation and forced controlled load combination, respectively. While the m-factor is equal to 1.5 in all other cases except in the case of moment resisting connections, the load increase factor will be 2.864.

For the floor areas outside the region that is immediately affected by the removal of structural elements, the following gravity load combinations are applied as per UFC Equation (3-10);

$$G = (0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S) \qquad (2)$$

In addition to gravity loads, the following lateral load is also applied at each floor level;

$$L_{lateral} = 0.002\Sigma P \tag{3}$$

where, ΣP is the sum of gravity loads acting at each floor level.

As for the case of simple beam connections, P-delta analysis with large displacement option will be applied to overcome the failed stability of the system. In this case the beam can act as steel wires hold the failure (Catenary Action).

b) Acceptable criteria. After column removal, the design of all elements is performed according to ANSI/AISC 360. The failed elements in both deformation control and force control models are redesigned repeatedly until structure stability of all members is accomplished.

The acceptable criteria of deformation controlled model (all beams are controlled by flexure or flexure with tension, and all columns' axial stress ratio is less than 0.5) as per Equation (3-13) of UFC09;

$$\Phi\ m\ Q_{CE} \geq Q_{UD} \tag{4}$$

where Φ is the strength reduction factor, Q_{CE} is the expected strength of the component or element for deformation-controlled actions and Q_{UD} is the deformation-controlled action, from Linear Static model. The expected strength is the lowest value obtained from the limit states of yielding, lateral-torsional buckling. For members subjected to flexure;

a. Q_{CE} is the plastic moment capacity, when the section is fully plastic.
b. When the element is subjected to lateral torsion buckling, then m in Equation (4) shall be replaced by m_e.

$$m_e = C_b\left(m - (m-1)\frac{L_b - L_p}{L_r - L_p}\right) \tag{5}$$

Where, L_b is the distance between points braced against lateral displacement of the compression flange, L_p is the limiting laterally un-braced length for full plastic bending capacity and L_r is the limiting laterally un-braced length for inelastic lateral-torsional buckling. L_p and L_r can be determined in accordance with LRFD Specifications Section F1. For members subjected to axial (compression) and flexure, Equations (5-10) and (5-11) in ASCE 41 is applied. For members subjected to axial (tension) and flexure Equations (5-13) in ASCE 41 shall be applied.

The acceptable criteria of forced controlled model (columns with axial stress ratio greater than 0.5 and belt truss elements controlled by compression force) as per Equation (3-14) of UFC09;

$$\Phi\ Q_{CL} \geq Q_{UF} \tag{6}$$

where Q_{UF} is the force-controlled action and Q_{CL} is the lower-bound strength of a component or element for force-controlled actions. The lower bound strength is the lowest value obtained from the limit states of column buckling, local flange buckling, or local web buckling and calculated according to Equation (5-12) of ASCE 41.

STUDY CASES

Initially, gravity and lateral loads (wind and/or seismic) are applied to the simply connected beam model (GRM), afterwards, the overall self weight of the designed building is calculated and the reference model is considered. According to APM approach, the possibility for diminishing PC can be accomplished by designing the structure such that it can bridge across the local failure area resulting from sudden column removal. This study investigates the robustness of five different structural systems, which are as follows;

a) SCM model: After one column removal, catenary action collapse resisted through tensile force in the surrounding elements, as shown in Figure 2a. To resist these huge tensile forces, bigger cross section beams are redesigned.

b) CRCM model: To enhance the behavior of SCM, the corner columns are rigidly connected to the adjacent beams. The PC resistance is slightly improved, but still this improvement may be neglected.

c) PRCM model: To gain additional enhancement in resisting the PC behavior, the number of the rigidly connected columns are increased. A substantial improvement is gained, as the beams will carry additional negative bending moment and less tension forces compared to the SCM and CRCM models.

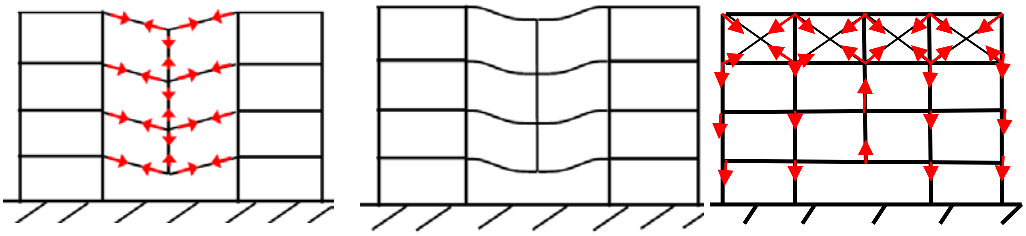
d) MRFM model: The flexural action presented in the rigidly connected frame structure will resist the PC through the bending response. APM will be applied and tangible` improvement is achieved. Refer to Figure 2b.

e) BTM model: When applying the belt Truss on top of the SCM model and one column is removed, the progressive collapse phenomenon stops. Successively, another load path will be found to redistribute the load. The columns above the removed element will reverse the load direction towards the belt truss, and the truss will redistribute the loads to the adjacent elements as shown in Figure 2c. This will lead to superior overall strength and progressive collapse resisting capacity.

It should be noted that according to Fig. 3.1 (Strategies for accidental design situations) in BS EN 1991-1-7, the proposed approach of using belt trusses to reduce the risk of PC in steel buildings, could be considered as being among the “strategies based on limiting the extent of localized failure”, through (1) enhanced redundancy e.g. alternative load paths, and (2) providing key element designed to sustain notional accidental action.

DISCUSSION OF RESULTS

A comparison study is conducted to find the optimum structural system that may be used to mitigate the PC. The guideline of UFC09 is applied. It can be observed from the results that the use of belt truss system plays a great roll in holding the initial failure of the damaged column and redistribute the resulting forces to the adjacent columns without affecting the beams’ straining actions. In case of SCM the huge tension forces induced in the beams as a result of the catenary action requires bigger beams’ section to resist PC. For MRFM the redistributed loads will be resisted by flexural action that results in bigger cross section of both beams and columns. It can be observed from Figure 3 that the weight increase percentage in case of MRFM is higher than that of SCM. It can be found also, that the PRCM model is the worst system to be applied, as the formed catenary action results in high tension forces on beams as well as an induced flexural stresses that required bigger beams and columns’ cross sections to resist the PC. The results indicated also that the BTM will enhance the vertical displacement at removed column than the other systems, as shown in Figure 4.



a) Catenary action: PC resisted through tensile force

b) Flexural action: PC resisted through bending response

c) Proposed: belt truss redistribute force of removed column

Figure 2. Progressive Collapse Design Approach

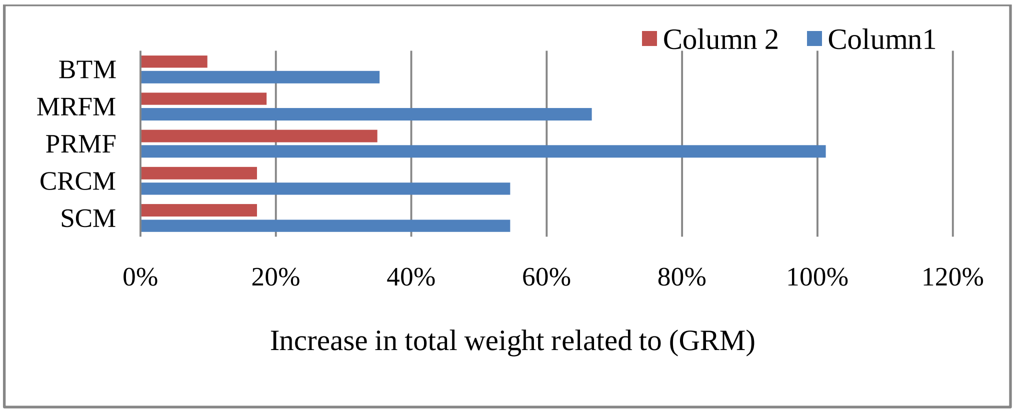


Figure 3. Persentage of steel weight increase relative to GRM model

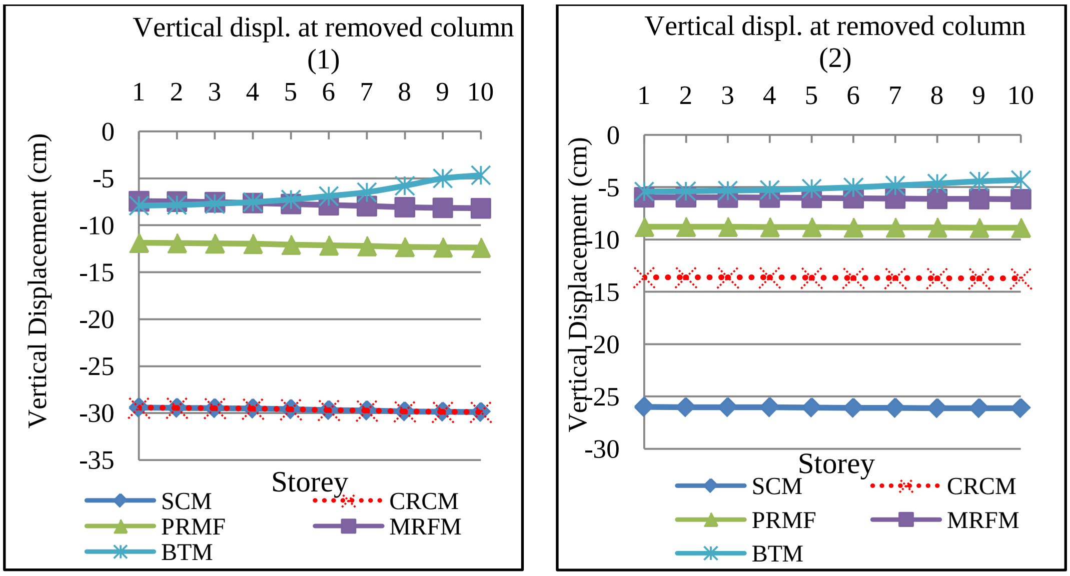


Figure 4. Vertical displacement at removed columns (1) and (2) for different models

SUMMARY AND CONCLUSIONS

The study focuses on the mitigation measures to reduce the risk of progressive collapse (PC) for steel mid-rise buildings. Five different structural systems are used to detect the most practical and cost effective system to enhance the PC resisting capacity. A3-d model is created using SAP2000 software package. The alternative Path Method approach specified by UFC09 is used. The five structural systems are investigated for two conditions, the first one when one of a perimeter middle column is removed, (column1), and the second when one of the corner column is removed (column2). The five structural models are redesigned to sustain the each column removal and compared with the calculated GRM weight.

Based on the studies performed, it could be concluded that one of the best practices to reduce the risk of PC, is the use of belt trusses at the top storey of the buildings. It is found that the percentage of weight increase in that case is 14% compared with the GRM whereas the increase is 55% in the case of SCM and 67% for the MRFM. It could also be concluded that; applying PRCM will result in a very small weight increase compared to design for other loads (≈ 101%), and the increase in vertical displacement at the removed column due to resisting of the PC is greatly enhanced in case of BTM rather than other structural systems.

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