

# Optimum belt truss locations to enhance the structural performance of high-rise steel buildings

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## Abstract

The race towards new building heights confronts numerous challenges. The main challenge that controls the design of a tall slender structure is the building drift. Another challenge confronting the designer is probably the robustness required to avoid progressive collapse due to localized failures in case of a column loss. The study investigates how to improve the building performance to overcome these challenges.

One of the most efficient and economical structural systems used to incapacitate these challenges is the use of belt trusses to provide a significant drift control through the tying of the peripheral columns enhancing in the process the building resistance to progressive collapse by means of holding the damaged elements' initial failure and redistributing the load supported by the failed elements. The optimum locations of the belt trusses still remain a crucial and also a pending question.

The study provides an answer to this question by demonstrating the results of a 25 storey steel building as a design example with belt trusses placed in different locations. The results indicate that both the drift and progressive collapse will be obviously enhanced merely by determining the optimum locations of belt trusses.

**Keywords:** Serviceability limits, Progressive collapse, Belt truss, Alternate Path Method, Robustness

## 1. Introduction

There are many design objectives for structural engineers to control the design of high-rise buildings such as safety, serviceability, durability, functionality, economic effectiveness, structural integrity and resistance to accidental actions. Nevertheless the main factors that still undermine the design are the building drift due to lateral loads, and the prevention of progressive collapse attributed to the accidental loads resulting in a column loss.

One of the most effective techniques that are likely applied in the design of high rise buildings is the use of belt trusses system. This system provides a significant control to the seismic response and drift for these buildings. Bayati, et al, (2008) and Gerasimidis, et al, (2009) studied the optimum location of multi-outriggers and belt trusses to reduce the seismic response and drift of the buildings.

The belt trusses placed on building's top roof and/or intermediate floor levels to resist the drift resulted from lateral loads have a significant effect on robustness enhancement. The high redundancy provided by the belt trusses are believed to mitigate progressive collapse and facilitate redistribution of forces away from the damaged area, they provide as well alternative load path to the damaged buildings, (Gibbons, 2003, and Tay et al, 2012). The approach of using belt trusses to reduce the risk of progressive collapse in steel buildings could be considered 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, BS EN (1991).

The approach of using the belt trusses system or any other structural approach should be governed by one major principle which is the optimum performance that may eventually affect not only the success but also the accomplishment of the project. The present research implements a basic design optimization study to prove that the belt trusses system is the structural approach that provides significant results. The study shall also, give an answer for the optimum locations of belt trusses system which represents a serious challenge for design engineers.

## 2. Numerical Model

### 2.1 Description of geometric model

The analysis model is a 25storey steel tower with a plan dimension of 30m × 30m, and a major grid spacing of 5.0m in both directions as shown in Figure 1. The first floor height is 6m, and the typical floor height is 4m. All gravity beams are joined with simple shear connections to columns. The lateral loads are sustained by a vertical K- system diagonal bracing arranged at the outer perimeter of the building as shown in Figure 2.b. The columns are supported at the base of the ground floor columns with simple base connection as shown in figure 1.a of the 3-D model that is created using SAP2000, CSI (2009) software package.

Structural steel members are taken as wide-flange shapes comprised of ASTM A992 steel  $F_y = 345$  MPa (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 bracing. The column cross sections are summarized in Table 1.

Table 1. Columns' cross-sections

Columns' group	Internal columns	Edge columns
Gr.1 ( at the 1 <sup>st</sup> floor)	W14X120	W14X90
Gr.2 (from 2 <sup>nd</sup> to 7 <sup>th</sup> floor)	W14X99	W14X61
Gr.3 (from 8 <sup>th</sup> to 12 <sup>th</sup> floor)	W14X61	W14X53
Gr.4 (from 13 <sup>th</sup> to 18 <sup>th</sup> floor)	W14X61	W14X38
Gr.5 (from 19 <sup>th</sup> to 25 <sup>th</sup> floor)	W14X43	W14X30

### 2.2 Load application

The analysis model is designed using dead (D) and superimposed loads (S) of 455 Kg/m<sup>2</sup>. The self-weight of the steel elements is included automatically by the program. The live load (L) is taken as 487 Kg/m<sup>2</sup>, as specified in ASCE 7-02 for office buildings. Wind and seismic loads are considered as specified in the UBC 97.

## 3. The Structural Design Models

The design of high rise steel buildings should be controlled by two main concepts. The first concept depends on all factors having the ability to carry the applied forces and cooperate successfully which can be indicated in design limit state, whereas, the second concept relies on human feelings such as deflection or drift which can be described as serviceability limit.

The design in this case is more often dictated by its serviceability rather than strength. Belt truss systems are generally very effective in fulfilling the serviceability requirements of tall buildings. Moreover, belt trusses have an effective rule in achieving the stability when the progressive collapse resistance is one of the design approaches.

The present study will investigate the belt trusses system optimum locations to mitigate the progressive collapse and also reduce the lateral drift. Several models will be applied to fulfill this requirement.

The reference model (case 0) is composed of simply connected steel elements that sustain gravity loads, while lateral loads are sustained by the vertical bracing at the building's outer perimeter.

For the remaining models additional belt trusses are considered at the building's outer perimeter to enhance the building performance. The different locations of the belt trusses are described as followings;

Case 1: Belt truss at the top floor only of building (at 25<sup>th</sup> floor level).

Case 2: Belt trusses at two successive storey height at the top of the building (at 24<sup>th</sup> and 25<sup>th</sup> floor levels)

Case 3: Belt trusses at top of building (25<sup>th</sup> Floor level) and on the upper third of building height.

Case 4: Belt trusses at top of building (25<sup>th</sup>) and on the lower third of building height.

Figure 1. Three dimensional model and exterior braced frame elevation of the building

Figure 1.a. Three dimensional model

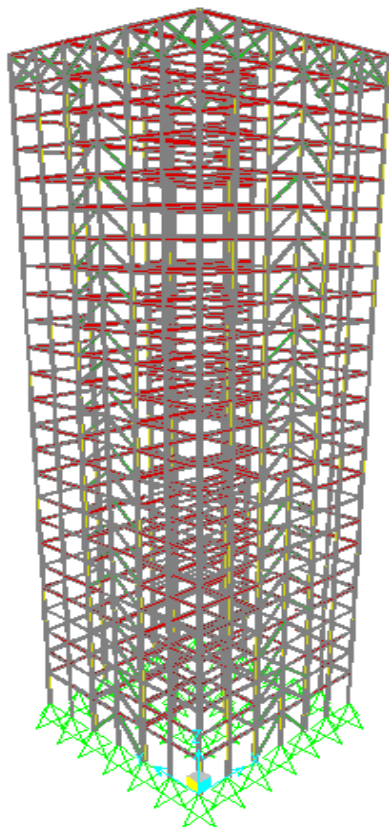
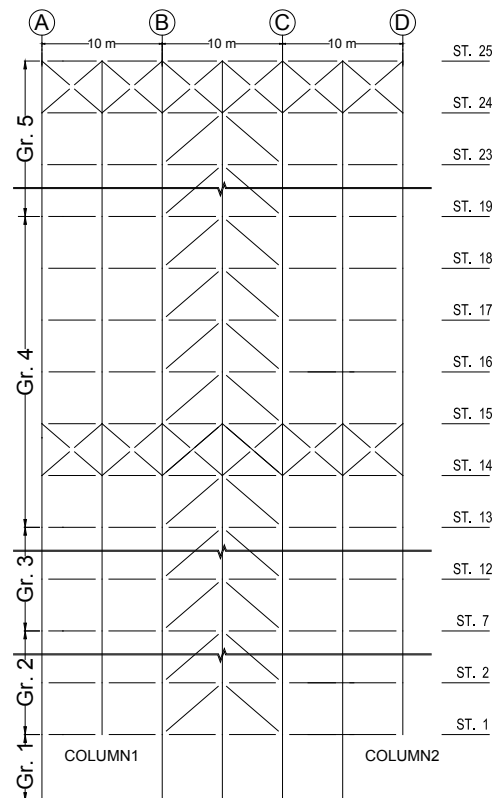


Figure 1.b. Exterior braced frame elevation



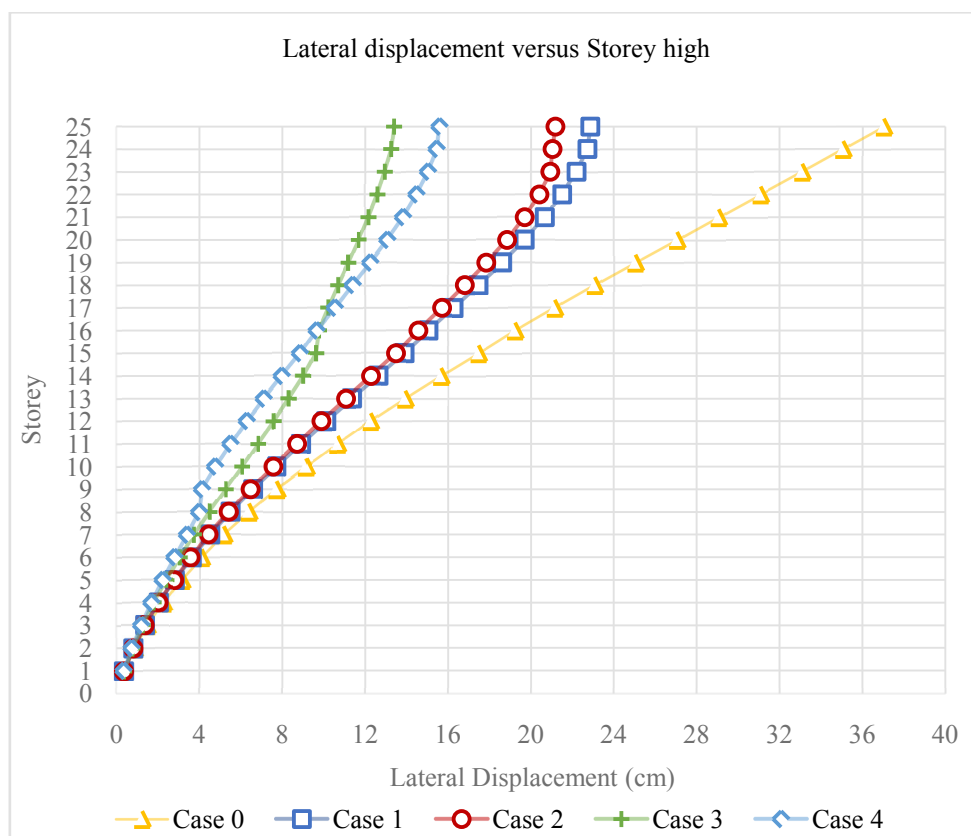
#### 4. Drift Analysis for the design models

Initially, both gravity and lateral loads (wind and/or seismic loads) has been applied to each model. The vertical loads applied on the slabs will be transferred to shear load resistance between beams and columns. The lateral loads will be resisted mainly by the vertical bracing system. The

belt truss system will provide a significant resistance to drift through the tying of the peripheral columns with the vertical bracing system. This system increases the lateral stiffness of the structure which will limit the induced drift.

The achieved results for the prescribed models are presented in Figure 2. The drift value for the reference model (case 0) will be considered as the reference value. The drift values for the prescribed belt truss cases (1 to 4) compared with the reference model will be reduced with the following ratios 40%, 43%, 64% and 58%, respectively. It can be concluded from the results that the optimum positions of the belt trusses are within the upper third of the tower.

Figure 2. Lateral drift for the different steel Structural systems



### 5. Progressive collapse analysis for the design models

The progressive collapse analysis for the five structural models has been investigated using the Alternate Path Method (APM) discussed by UFC09 code. The APM is well applicable to investigate the ability of structure to bridge the located failed elements. The analysis will consider the removal of two ground floor columns on the building perimeter, one at a time. One of the removed columns is an interior on the building premier (column1) and the other column is at the edge of the building (column 2). A 3-D finite element model is performed using SAP2000, CSI (2009) software package.

The study will follow the linear static analysis mentioned in UFC09 that has special factors in combination to take the effect of material nonlinearity and the dynamic effect of progressive collapse. The GSA (2003) and the DoD (2005) guidelines proposed an amplification factor of 2 for the linear static analysis to account for dynamic redistribution of forces. The load combination of

the GSA-2003 for static analysis is  $2(\text{Dead Load} + 0.25 \times \text{Live Load})$  and that of the DoD-2005 is  $2(1.2 \times \text{Dead Load} + 0.5 \times \text{Live Load}) + 0.2 \times \text{Wind Load}$ . The amplified load is applied only for floor areas that are immediately affected by the removed element. As for the floor areas outside the region that is immediately affected by the removal of structural elements, the applied gravity load (G) combinations is  $(1.2 \text{Dead load} + 0.5 \text{Live load})$

In addition to gravity loads and the effect of P-delta, a lateral load is also applied at each floor level which is equal to  $0.002 (G = \text{sum of gravity loads acting at each floor level})$ .

### 6. Scenarios for sudden columns' loss

To find out the optimum number and locations of belt trusses (BT) to reduce the effect of progressive collapse, the five prescribed structural models has been examined by removing two exterior columns, one at a time. Column 1 is an interior column and column 2 is a corner one. After each column removal, the design of each steel element is performed according to ANSI/AISC 360. The failed elements are redesigned and enlarged repeatedly until the structure stability is achieved.

The main philosophy of APM is bridging the loads across the local failed area and redistributing it to the adjacent elements. In the present study, all the beams are simply connected to columns. In the reference model (case 0), the sudden column loss will result in applying the catenary action that will produce excessive tensile forces in the surrounding beams, as shown in Figure 3.a. The adjacent beams are enlarged until the structural stability is achieved. The steel tonnage for this case is determined and considered as a comparison reference weight. The BT located on top of the building as well as another BT located at different floor levels enhanced the building robustness through the forces redistribution as shown in Figure 3.b.

To investigate the optimum BT locations, the four pre-described model systems (case 1, 2, 3 and 4) has been subjected to sudden loss of two columns, an interior column (column1) and a corner column (column2). In each case the adjacent elements to the failed column are redesigned and their cross sections are increased repeatedly to achieve the safety requirements, and for each case the tonnage is calculated and compared with the reference model (case 0). The tonnage comparison is plotted in Figure 5.

The deformed shape of the model systems after each column loss is shown in Figures 4.a and 4.b, respectively. The vertical displacements at the location of the removed column is plotted in Figures 6, 7 for column 1 and 2 respectively

The results indicate that the nearest BT to the removed column is the best location for resisting the PC as the failed column load will be transmitted to the nearest BT.

Figure 3. Sudden columns' loss scenarios

Figure 3.a. Progressive collapse resisted through tensile forces in adjacent beams

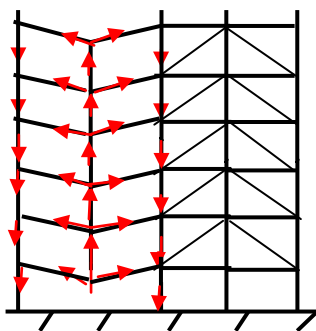


Figure 3.b. Belt truss redistribute induced forces due to column loss

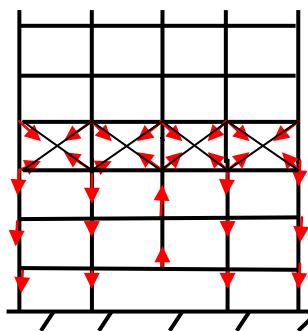


Figure 4.a. Deformed shape after column 1 sudden loss

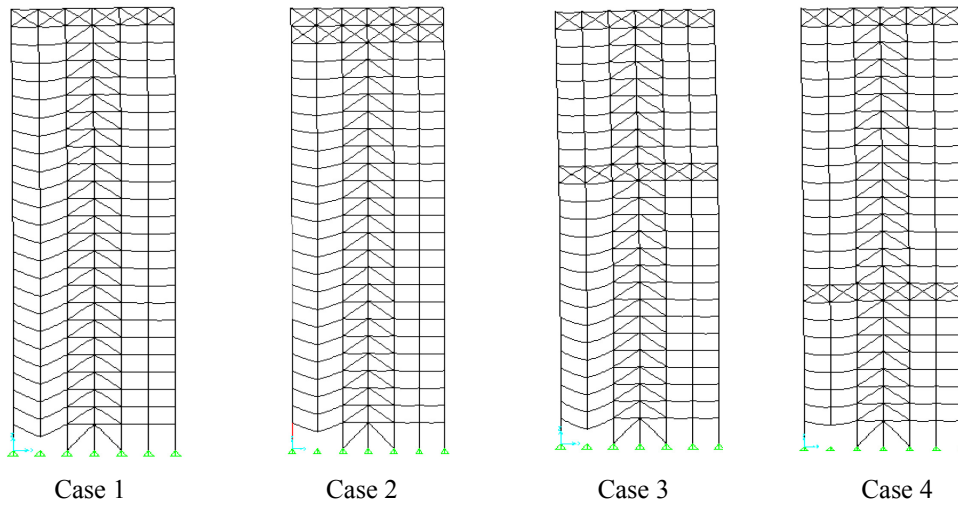


Figure 4.b. Deformed shape after column 2 sudden loss

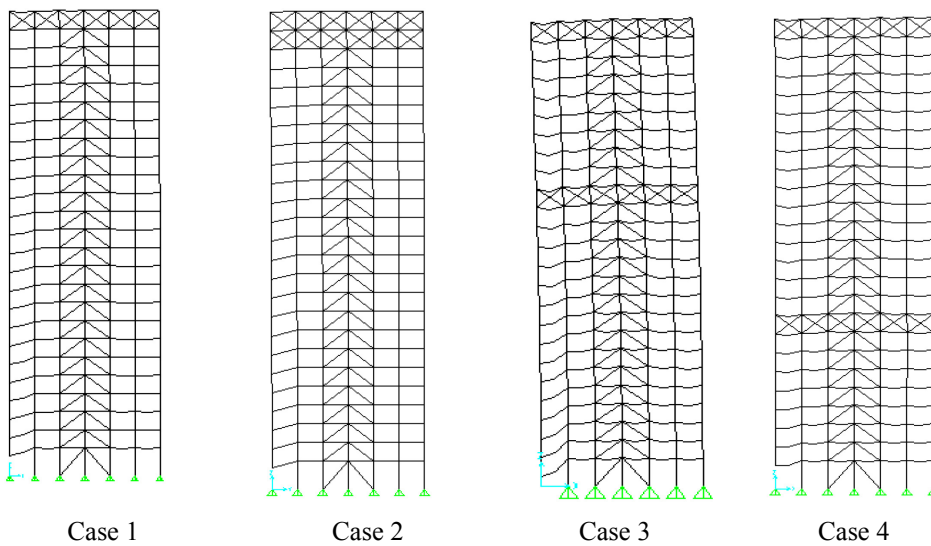


Figure 5. Percentage of steel weight increase relative to (case 0) model

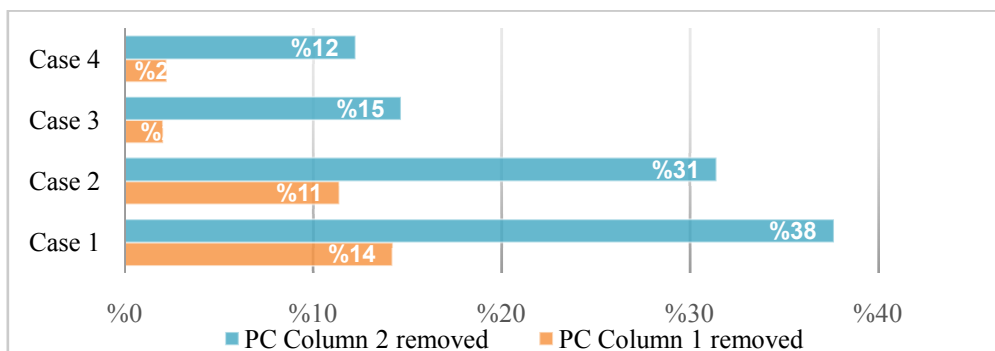


Figure 6.a. Vertical displacement at removed columns (1)

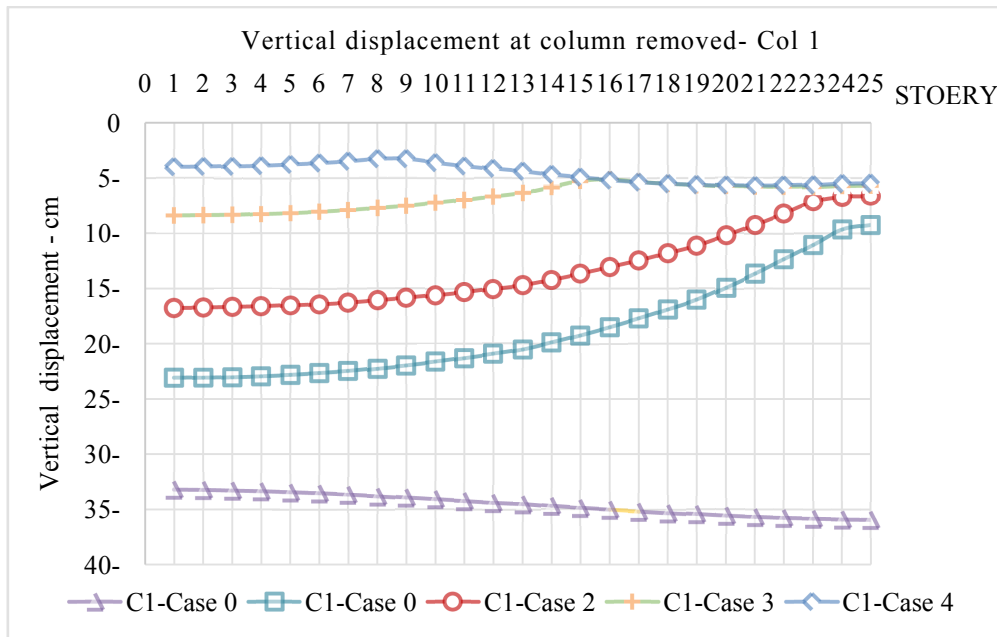
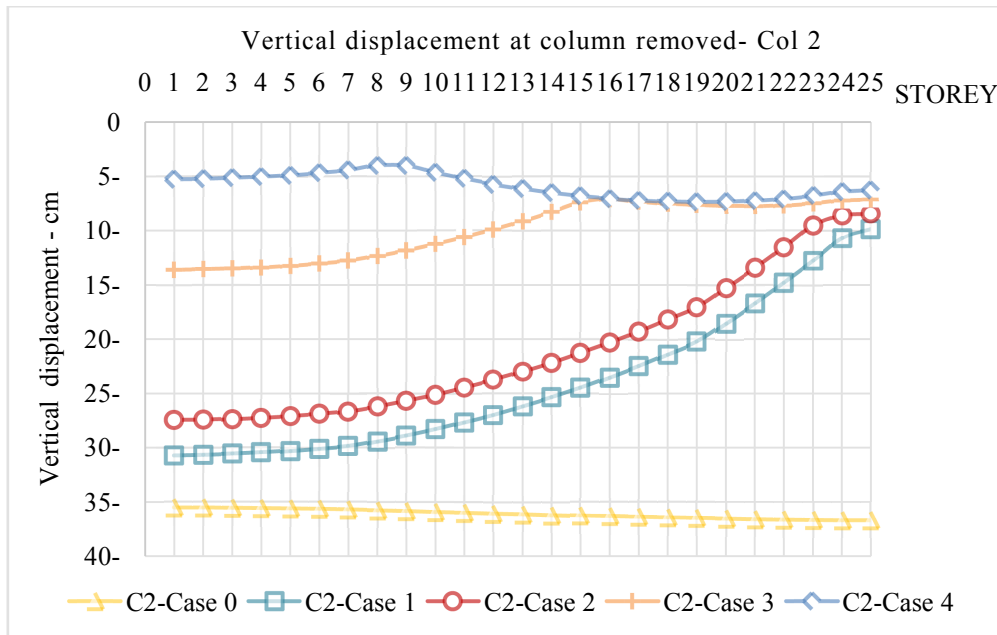


Figure 6.b. Vertical displacement at removed columns (2)



**7. Conclusions**

It can be concluded from the previous results that the optimum location for the belt trusses system to overcome the drift is to be within the upper third of the building. It can be also concluded that the optimum location for the BT to resist the progressive collapse are the nearest location to the failed column. It should be noted that for most of the sudden column collapses as a result of unexpected events has occurred are happened to the lower ground columns, this is attributed to the fact that, they have the higher stresses and are easily achieved. Therefore, the optimum position for

BT to resist the progressive analysis is within the lower third of the building. To resist both the drift and PC it is recommended to distribute the BT within both the lower and upper thirds of the structure.

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