Evaluation of Bracing System for a Multi-Story Steel Building Subjected to Missing Column Scenario

Alina Sajid[1], Jaweria Khan[2]
[1]Department of Civil Engineering
Mirpur University of Science & Technology
Pirzadaalina7@gmail.com

[2]Department of Civil Engineering
Mirpur University of Science & Technology
Jaweriakhan.ce@gmail.com

ABSTRACT

There have been many examples of buildings in the past that have been subjected to progressive collapse due to the failure of one or more critical columns e.g. the fall of the Twin Towers of the World Trade Center in 9/11. The city of Mirpur, AJK, lies in Seismic Zone 3, and many past earthquakes have damaged the city severely resulting in the progressive collapse of many buildings. The missing column scenario represents a critical column that has been damaged by any unexpected loading and could lead to the progressive collapse of the building. The goal is to use the alternate load path method to divert the load of the damaged column to the remaining members. This study focuses on the design of an irregular multi-story steel building, specifically evaluating different bracing systems for such a building facing a missing column scenario. The Static Equivalent Lateral Force analysis is used for the study by using the ETABS software. By applying the missing column scenario, testing is done on three different bracing systems (eccentric bracing, inverted V bracing, and X-bracing) to ensure the stability of the structure. The results of the different bracing systems are compared using total roof lateral displacement, Deflection, and Beam-Column capacity ratio as failure criteria. Based on these criteria, X-bracings are proved to be the most suitable type of bracings in providing alternate load path and ultimately stabilizing the structure.

Keywords: *Progressive collapse, Alternate load path method, Deflection, Beam-column capacity ratio, Bracing*

1. Introduction:

A structure may experience unanticipated loads during its lifespan, leading to gradual failure. When a structure loses one or more of its major load-bearing columns—its critical columns— adjacent structural parts also fail, which ultimately leads to the collapse of the entire building. In general, steel structures are susceptible to the risk of progressive collapse. This loss could be brought on by an unforeseen event, such as a car accident, earthquake, explosion, terrorist attack, or construction mishap.

Countless past building failures together with some recent building collapses have shown that buildings designed according to current building codes are not resilient enough to withstand unexpected loads and fail progressively. The gas explosion of the Ronan Point Building in the UK in 1968 [1], the bombing of the Murrah Federal Building in the US in 1995 [2] and the collapse of the World Trade Center in the US in 2001 [3] [4] are examples of actual progressive collapse instances for existing buildings. A recent example of critical member failure is the 12story Champlain Towers South, Florida, USA [5]. The collapse occurred on June 24, 2021, killing 98 people and its cause is currently under investigation. Critical members' collapse leading to progressive failure mitigation has become an urgent demand in the civil engineering field especially after the 9/11 event.

Pakistan is a region of extreme seismicity which bears earthquakes of different magnitudes. The earthquake of 2005, October 8th, caused significant damage in Azad Jammu Kashmir [6]. The town of Balakot was nearly totally devastated, while Muzaffarabad had the most fatalities. Many buildings collapsed due to the failure of the critical members.

The focus of our project is to minimize the structural damage caused by unexpected loads using the column removal scenario and alternate load transferring path method. An alternate load path is given to prevent excessive overall collapse under accidental loading. This is achieved by providing bracings or shear walls. It is a very good practice in steel structures and is very economical. We will design and analyze an irregular steel building with the help of ETABS software. Then, we will use the missing column scenario on the designed building to see how it will perform under any unexpected loading. The end goal is to provide structural bracing to the critical column of the building which will divert the load path and provide lateral stiffness and stability to the structure.

2. Literature Review

The failure of critical members is a serious concern in structural engineering because it can cause progressive collapse of the entire building. A critical column plays a very important role in supporting the entire structure, and its failure due to any dynamic loading e.g. earthquake, explosion, or construction error can set off a domino effect that will cause severe damage to the other elements of the structure. Some of the major incidents involving such failures have been shown in the table below. These structural failures have brought to light the necessity of structural designs that take this into account, underscoring the significance of constructing structures that are able to redistribute loads if a critical column is damaged.

Table 2.1 Progressive collapse of buildings and their causes [1] [2] [3] [5] [7]

Sr. No.	Building Name	Location	Date	Collapse Cause of Building
1	Windsor Tower	Madrid, Spain	Feb, 2005	Fire event
2	St Mark's Campanile	Venice, Italy	July,1902	Fire event
3	Ronan Point Apartment	London, United Kingdom	May, 1968	Gas explosion
4	Skyline Towers Building	Verginia, United States	March, 1973	Early framework Removal
5	Civic Arena Roof	Kansas, United States	1978	Heavy snow load
6	World Trade Center	New York, United States	Sept., 2001	Terroristic attack
7	Ancient Bell Tower	Goch, Germany	1992	Bell dynamic effects
8	Khobar Towers	Saudi Arabia	1996	Terroristic attack
9	Murrah Federal Building	Oklahoma, United States	April, 1995	Terroristic attack

One approach to preventing catastrophic collapse when a critical column fails is creating an alternate load path. This approach ensures that, when a critical column fails, the loads it formerly supported are redistributed to other members of the structure, allowing the building to remain stable. Izzuddin and colleagues (2008) demonstrated that buildings designed with alternate load paths are significantly more resilient to localized failures, as these paths enable the redistribution of loads without overstressing adjacent members [7]. In seismic prone areas of Pakistan, where earthquakes are very frequent, bracing systems prove to be efficient solution in providing alternate load paths and stabilizing the structure. Mahmoudi and Mohammadpour (2011) found X-bracing to be particularly effective in minimizing deflections and maintaining structural stability under critical column failure scenarios [8]. Research shows that Inverted V bracing improves stability by distributing forces symmetrically, minimizing stress concentrations, and maintaining uniform deformation under seismic loads (Razak et al., 2018) [9]. Eccentric bracing, on the other hand, is particularly effective at absorbing seismic energy through flexural and shear zones created by its offsets (Elsanadedy et al., 2022) [10]. These systems were chosen for their demonstrated ability to enhance the building's resilience against progressive collapse while maintaining structural stability.

While critical column failure and the alternate load path have a strong body of research behind them, there are still several significant gaps. Most of the research now in publication concentrates on typical, regular building designs, leaving a gap when it comes to understanding how irregular buildings respond when a critical column fails. When met with such failures, buildings with complex geometries, unusual layouts, or locations in seismic zones may respond quite differently from more traditional designs. Few research has examined the application of the alternate load path method in more complex building layouts, with the majority focusing on conventional steel structures. In areas like Pakistan, where earthquakes are common and it is crucial for buildings to withstand seismic loads, this gap is especially apparent.

The aim of this study is to focus on the performance of three different bracing systems in irregular multi-story steel building when subjected to missing column scenario. Much research has been done on regular steel buildings but there is limited knowledge of performance of different bracing system in irregular steel buildings. By performing static equivalent lateral force analysis of irregular steel building integrated with different bracing system such as eccentric bracing, inverted V bracing and X bracing provide clear picture of which system offer most effective redistribution of load and give overall stability to the building when subjected to missing column scenario.

This study will compare three bracing systems based on key criteria such as total roof displacement, deflection and beam column capacity ratios. This research will offer unique techniques of alternate load path methods for preventing catastrophic collapse of the steel structures. This study addresses the different challenges such as blasts and earthquakes posed by irregular structures and offers practical guidance for engineers and designers in the field.

3. Methodology:

The study assesses the effectiveness of three bracing techniques in a multi-story steel building that is exposed to a missing column scenario using a quantitative approach. The building model is designed and analyzed using ETABS software, using material properties and structural design based on the most recent AISC Steel Construction Manual and ACI 318-19 [1]. The Static Equivalent Lateral Force Method in accordance with ASCE 7-22 [12] is applied to calculate seismic loads. The Static Equivalent Lateral Force Method, as per ASCE 7-22, calculates seismic forces by applying a base shear proportional to the building's weight and site-specific seismic conditions. This force is then distributed along the building's height based on mass and stiffness, with factors like the response modification factor (R) and importance factor (I) adjusting for inelastic behavior and the structure's criticality. It is typically used for low- to mid-rise buildings. To gather data, simulations are used to calculate beam-column capacity ratios, roof displacement, and deflection in both scenarios where the critical column is present and not. The three bracing systems—eccentric, inverted V, and X-bracing—are tested sequentially. To evaluate the bracing systems' efficiency in distributing loads and preserving stability, each scenario is examined. Based on adherence to the most recent engineering codes, the outcomes are compared to ascertain the bracing method that is most viable.

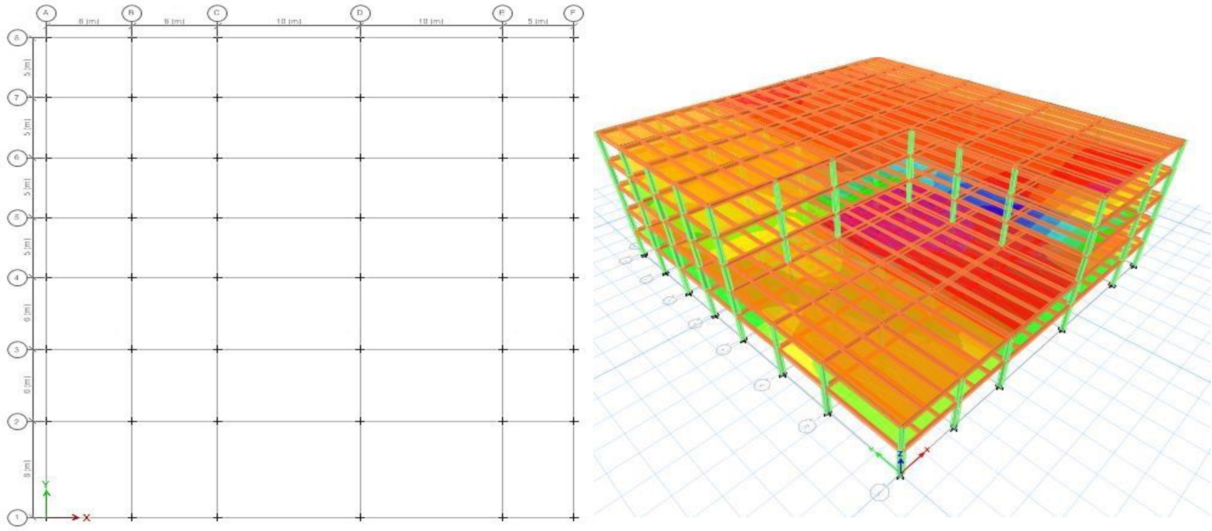


Figure 3.1. Building Plan and 3D Model

Table 3.1 Design parameters

Parameters	Values
Response Modification Factor (R)	8
Importance Factor	1
Damping Ratio	5%
Material Steel	A36
Load Cases	Dead, Live, EQX & EQY

4. Results and Discussions:

Scenario 1: Initial Building Design

The initial design and analysis of the building were conducted to ensure that all structural members adhered to the required deflection limits and beam-column capacity ratios (PM ratios). Several iterations were performed to adjust the design, ensuring that all sections met the necessary AISC and ACI code standards. Once the final design was completed, all members passed the structural checks, with the assigned sections for beams and columns documented in Table 4.1.

Scenario 2: Critical Column Removal

In the second scenario, the removal of a critical column in the basement was simulated to represent unexpected damage. The analysis revealed that several adjacent members failed due to the redistribution of loads, demonstrating the building's susceptibility to localized failures. This scenario highlighted the potential for progressive collapse in the absence of adequate structural reinforcement.

Scenario 3: Bracing Systems

To mitigate the effects of the missing column, three types of bracing systems—eccentric, inverted V, and X-bracing—were applied in sequence. Each bracing system was analyzed, and the results showed that the X-bracing system provided the most effective reduction in deflection and improved overall stability. This system proved to be the most efficient in redistributing the loads and preventing further failure (Table 4.2).

4.1 Results:

1- After analyzing and designing the steel building, all members passed the checks, and the design met standards. Beam and column sections were assigned as shown in Table 4.1, with the final design illustrated in Figure 4.1.

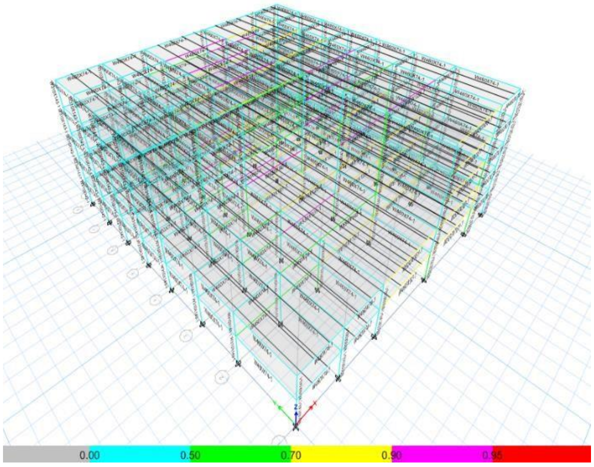


Figure 4.1 Result of Scenario 1

Table 4.1 Selected Sections of Beams and Columns

Beams	Columns
W460 X 74	W360 X 196
	W360 X 382
	W310 X 158
	W360 X 216
	W310 X 143
	W360 X 287
	W360 X 634
	W360 X 609

2- The critical basement column was removed, and the analysis was repeated. The results showed that two beams (B24 and B25) on the fifth story and five columns failed due to exceeding deflection limits, as illustrated in Figure 4.2.

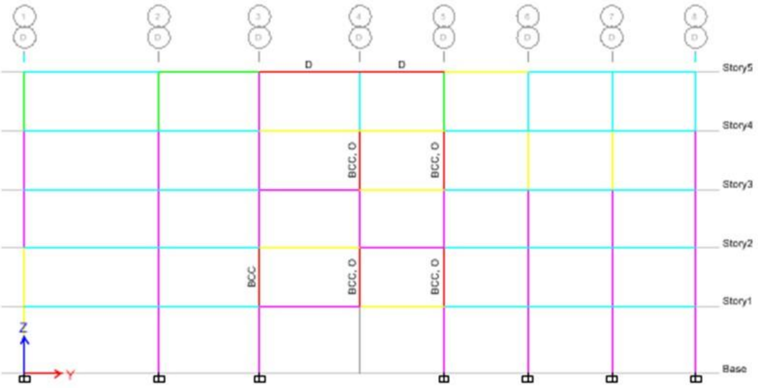


Figure 4.2 Failed Beams and Columns (Red Coloured)

Columns C28 and C29 on the fourth story, as well as columns C27, C28, and C29 on the second story, failed due to a beam-column capacity ratio greater than 1, as detailed in Table 4.2.

Table 4.2 BCC Ratios & Deflection Values

Columns	Beams	Story	Deflection mm	Deflection Limit	BCC ratio	Status
C27		2	-	-	1.000	Not OK
C28		2	-	-	1.015	Not OK
C29		2	-	-	1.024	Not OK
C28		4	-	-	1.095	Not OK
C29		4	-	-	1.000	Not OK
	B24	5	29.5	25		Not OK
	B25	5	26.9	20.8		Not OK

3- Different types of bracings were applied to the critical basement column, and the building was reanalyzed. The results showed that all previously failed beams now passed the design checks.

4.2 Type 1: Eccentric backward and forward bracing Results

Eccentric backward and forward bracings were added, and the building was reanalyzed. The results indicated that all previously failed beams and columns now passed. Beams B24 and B25 on the fifth story met deflection limits as shown in figure 4.3.

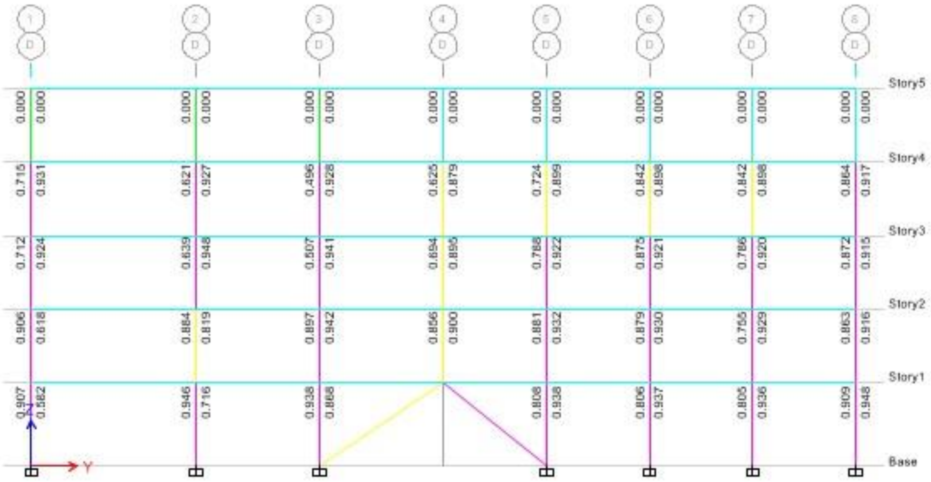


Figure 4.3. Type 1: Eccentric backward and forward bracing & Beam Column Capacity Ratios

Columns C28 and C29 on the fourth story, as well as columns C27, C28, and C29 on the second story, passed with a beam-column capacity ratio of less than 1, as shown in Table 4.3.

Table 4.3 BCC Ratios & Deflection Values (Eccentric Bracing)

Columns	Beams	Story	Deflection mm	Deflection Limit	BCC ratio	Status
C27		2	-	-	0.942	OK
C28		2	-	-	0.9	OK
C29		2	-	-	0.932	OK
C28		4	-	-	0.879	OK
C29		4	-	-	0.899	OK
	B24	5	1.6	25		OK
	B25	5	0.8	20.8		OK

4.3 Type 2: Inverted V bracing Results

Inverted V bracings were introduced, and the building was reanalyzed. The results showed that all previously failed beams and columns now passed the design checks. Beams B24 and B25 on the fifth story met deflection limits, as illustrated in Figure 4.4.

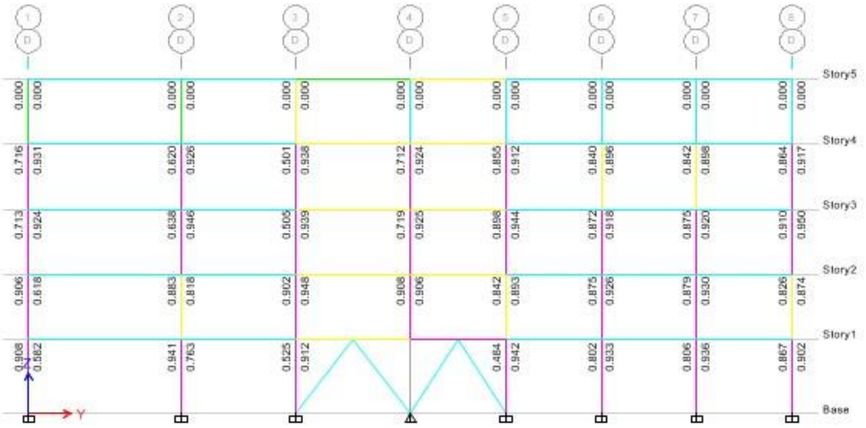


Figure 4.4 Type 2: Inverted V bracing & Beam Column Capacity Ratios

Columns C28 and C29 on the fourth story, as well as columns C27, C28, and C29 on the second story, passed with a beam-column capacity ratio of less than 1, as shown in Table 4.4.

Table 4.4 BCC Ratios & Deflection Values (Inverted V Bracing)

Columns	Beams	Story	Deflection mm	Deflection Limit	BCC ratio	Status
C27		2	-	-	0.948	OK
C28		2	-	-	0.906	OK
C29		2	-	-	0.893	OK
C28		4	-	-	0.924	OK
C29		4	-	-	0.912	OK
	B24	5	16.6	25		OK
	B25	5	14.9	20.8		OK

4.4 Type 3: X bracing Results

Cross bracings were applied, and the building was reanalyzed. The results showed that all previously failed beams and columns now passed the design checks. Beams B24 and B25 on the fifth story met deflection limits, as shown in Figure 4.5.

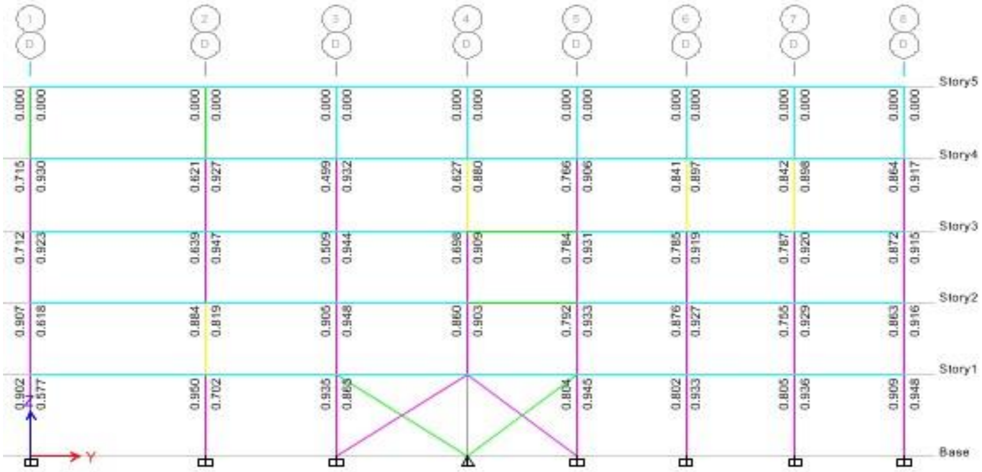


Figure 4.5 Type 3: X bracing results & Beam Column Capacity Ratios

Columns C28 and C29 on the fourth story, as well as columns C27, C28, and C29 on the second story, passed with a beam-column capacity ratio of less than 1, as shown in Table 4.5.

Table 4.5 BCC Ratios & Deflection Values (X-Bracing)

Columns	Beams	Story	Deflection mm	Deflection Limit	BCC ratio	Status
C27		2	-	-	0.948	OK
C28		2	-	-	0.903	OK
C29		2	-	-	0.933	OK
C28		4	-	-	0.880	OK
C29		4	-	-	0.906	OK
	B24	5	1.9	25		OK
	B25	5	1	20.8		OK

4.5 Roof Lateral Displacement in the Structure

To compare the different scenarios, we assessed the roof lateral displacement at the corner of the top story. The maximum displacement of 31.7 mm occurred when the column was removed, while the minimum displacement of 25.1 mm was achieved with cross bracing. All roof lateral displacement values are detailed in Table 4.6, and a bar chart illustrating these values is provided in Graph 4.1. Additionally, the deflection limit was calculated using the formula: Height of Building (inches) / 400. For a building height of 709 inches, this results in a deflection limit of 45 mm.

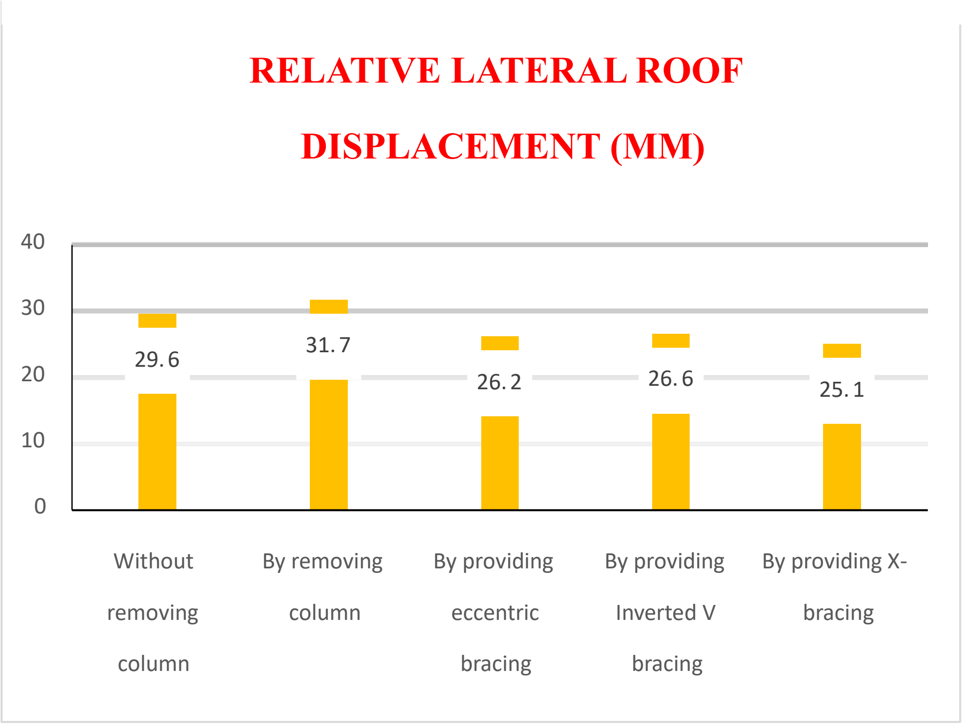
Height of Building (inches) / 400

709 / 400 = 1.77 Inches = 45mm

Table 4.6 Roof Lateral Displacement Values

Scenarios	Roof lateral displacement (mm)	Displacement limit (mm)
Without removing column	29.6	45
By removing column	31.7	45
By providing eccentric bracing	26.2	45
By providing Inverted V bracing	26.6	45
By providing X-bracing	25.1	45

Table 1 Roof Lateral Displacement



5. Conclusion:

By comparing the results of the three different types of bracings:

- The minimum deflection values of B24 and B25 are 1.9 and 1 mm respectively when used X-Bracing.
- The least roof lateral displacement value of 25.1mm was observed when X-bracing was used.

Based on these criteria, X-bracing has proven to be the most suitable type for ensuring an alternate load path and effectively preventing progressive collapse in multi-story steel structures.

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