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# Optimizing Base Shear Contributions in Steel-Braced RC Frames for Improved Seismic Performance

**Birendra Kumar Bohara**[1*]
[1]Assistant Professor, Far Western University, Nepal, bbohara2@gmail.com
[*]Corresponding author, e-mail: bbohara2@gmail.com

**Abstract—** This study investigates the seismic performance of reinforced concrete (RC) frames retrofitted with V-shaped steel bracing through a comparative analysis using Response Spectrum Analysis (RSA). A total of 24 models, 12 braced and 12 unbraced, were analyzed for 4-, 8-, 12-, and 16-story buildings, considering three base shear contributions (25%, 50%, and 75%) in columns observed. Key seismic parameters, including fundamental time period (FTP), top-story displacements, inter-story drift (ISD), base shear, and stiffness, were evaluated. Results demonstrate that V-bracing significantly improves seismic performance in low- to mid-rise buildings by reducing FTP (up to 76%), displacements (up to 72%), and ISD while increasing base shear demand (up to 59%) and structural stiffness. Higher base shear contributions in columns (e.g., 75%) led to increased displacements and reduced base shear, indicating a trade-off between column and bracing resistance. The findings highlight the effectiveness of steel bracing in retrofitting RC structures, with optimal performance observed when bracing resists a larger share of lateral forces. This study provides insights for seismic design and retrofitting strategies, emphasizing the role of dual systems in enhancing earthquake resilience. Further nonlinear analysis is recommended to explore post-yield behavior.

*Keywords: Steel bracing, RC frames, seismic retrofitting, response spectrum analysis, base shear.*

## 1. Introduction

India's high seismic vulnerability necessitates robust earthquake-resistant construction practices[1]. Situated in a seismically active zone, the country has witnessed devastating earthquakes that exposed structural deficiencies in many buildings [2]. These events highlighted the urgent need for effective retrofitting solutions, particularly for existing reinforced concrete (RC) structures that were designed using outdated codes or poor construction practices [3]. Among various retrofitting techniques, steel bracing systems have emerged as a particularly effective solution due to their ability to significantly enhance a building's lateral load resistance while being relatively economical and minimally disruptive to implement [4], [5], [6].

The importance of retrofitting becomes evident when considering several critical scenarios: when seismic design codes are updated, when buildings undergo functional changes that increase their load demands, or when structural deficiencies are identified in existing constructions [7], [8], [9]. Traditional RC frames often lack sufficient lateral stiffness, making them vulnerable to excessive drifts and potential collapse during earthquakes. Steel bracing addresses these limitations by providing additional stiffness and strength, effectively reducing inter-story drifts and improving overall seismic performance [10]. The V-

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shaped bracing configuration offers particular advantages, balancing structural efficiency with architectural flexibility, unlike X-bracing which can obstruct openings and passageways [11], [12].

Extensive research has demonstrated the effectiveness of steel bracing systems. Early experimental work by Maheri and Sahebi [13], [14], [15], [16] established the fundamental benefits of steel bracing in RC frames, showing significant improvements in load capacity and displacement control. More recent investigations by Rahimi and Maheri (2018-2020) [13], [17] focused specifically on X-bracing systems, providing valuable insights into their behavior but also identifying challenges related to buckling and connection details [18], [19], [20]. While these studies have contributed substantially to our understanding of braced systems, most have been limited to two-dimensional analyses or specific bracing types, leaving gaps in our knowledge about three-dimensional behavior and alternative bracing configurations [21], [22].

This study addresses these research gaps by focusing on V-shaped steel bracing in three-dimensional RC frames, employing Response Spectrum Analysis to evaluate seismic performance across a range of building heights (4 to 16 stories). The investigation considers three distinct base shear distribution scenarios (25%, 50%, and 75% resisted by columns) to optimize the dual-system design approach recommended by IS 1893 (2016) [23]. The analytical models incorporate realistic material properties (M25 concrete, Fe415 reinforcement, and Fe250 steel bracing) and loading conditions representative of Indian seismic zones (Zone V with Z=0.36). By comparing braced and unbraced frames, the study quantifies improvements in key performance parameters including fundamental time period, story displacements, inter-story drift, and base shear capacity.

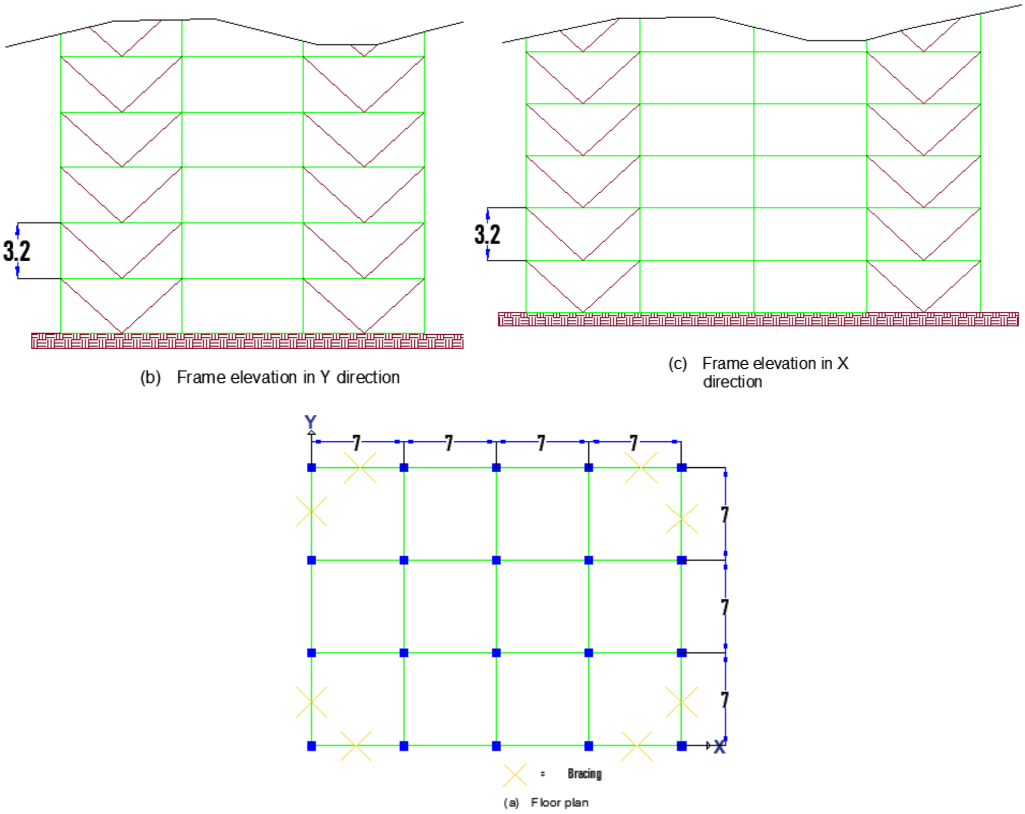
While the current study focuses on linear dynamic analysis, future research directions should include nonlinear analyses (such as pushover and time-history methods) to better understand post-yield behavior and failure mechanisms. Experimental validation through physical testing would further confirm the analytical findings, and detailed cost-benefit analyses would help establish the economic viability of different retrofitting approaches. Nevertheless, the current results clearly establish steel V-bracing as a powerful tool for enhancing seismic resilience in RC buildings, offering a practical path to safer structures in India's earthquake-prone regions. By combining analytical rigor with practical design considerations, this research contributes to the ongoing effort to mitigate seismic risks and protect lives and infrastructure in vulnerable areas.

## 2. Method

Low to mid-rise 3D buildings are studied by using the ETABS finite element software. Four-story, eight-story, twelve-story and sixteen-story buildings are analyzed in Etabs software by using RSA. Steel braced and unbraced frames are modeled, and by using the RSA, the result is made based on the observation of displacement response, drift response, base shear, natural time period, and stiffness of the building. Each four different story height buildings has three cases (25, 50, and 75% base shear contribution in the columns). A comparative observation is made to understand the efficiency of the RC building with steel bracing.

All models have a 7m center-to-center span in both the X and Y direction of the plan, and the story height of the structure is 3.2m. The outer frame of the buildings consists of steel bracing resisting the lateral load. The plan view and elevation in each direction are given in Fig. 1. The modeled RC frame with and without steel V-braced frame is shown in Fig. 2.

In all models, the steel V bracing is used and the RC beam slabs and columns are designed considering a 'compressive strength for the concrete' is 25MPa. The yield strength of the rebar is considered as 415MPa, and the yield strength of the steel bracing is assumed as 250MPa of each model. According to the Indian seismic code, the response reduction factors are considered as 4.5 and 5% damping for the models. The zone factors are taken as 0.36 and 1 is the importance factor for the models. In all the models of the 5 kN/m2, the live load is considered each floor except the top floor, in the top floor, it is considered as 2 kN/m2. Also superimposed dead load is considered as 2.5 kN/m2.



(b) Frame elevation in Y direction

(c) Frame elevation in X direction

(a) Floor plan

Figure 1. Geometrical plan shape and elevation of the models.

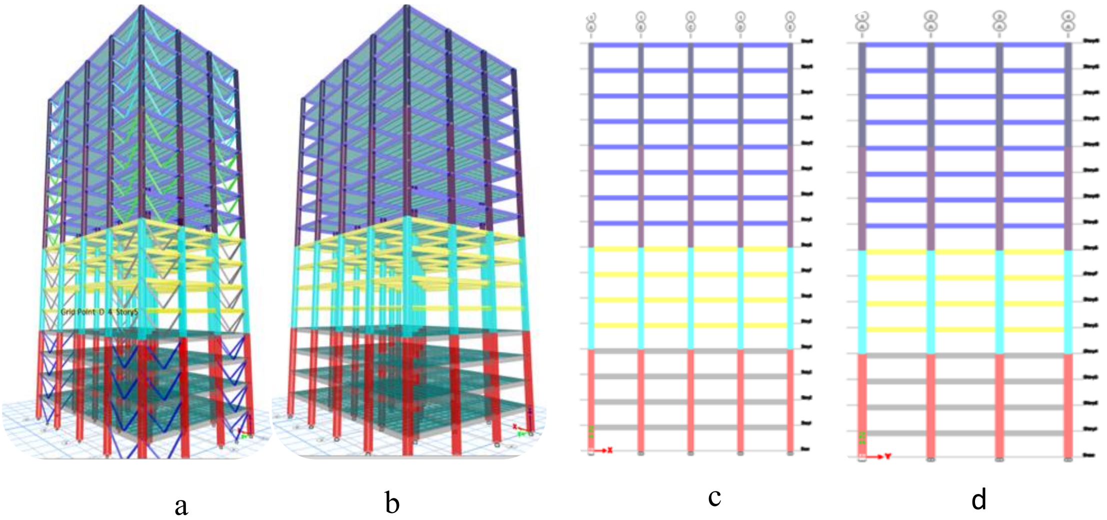


Figure 2. Modeling of 16 16-story building a) 16-story (16X) 3D with V-shape steel bracing frame, b) 16 story 3D without steel bracing, c) along X direction without bracing, d) along Y direction without bracing

The design of the member is done such that columns are resisted base shear according to the three cases (25%, 50% and 75%) of each story building. For this, the bracing is designed such that it resists the base shear according to the case study. After the design of the bracing, the beam is designed then the columns are designed. To reduce the strength of every 4 stories, the cross-section of the columns and beams are changed. The steel bracing also changes thickness every four stories of each model. To avoid the local buckling, the box cross-section is used for steel v-bracing.

To understand every 24 models, each model is named as NdV where the N represents the story number, such as 4 stories, 8 stories, 12 and 16 stories. Where d represents each X-axis and Y-axis and V represents the base shear contribution (25, 50, and 75%) of each model.

The structural design methodology for this study strictly adheres to Indian standard code provisions, with IS 1893:2016 (Part 1) [23] governing the seismic design of RC dual systems incorporating steel bracing, and IS 456:2000 specifying the design requirements for reinforced concrete members. As per IS 1893:2016 provisions for dual systems, the moment-resisting frame (columns) must be designed to resist a minimum of 25% of the total base shear, while the remaining lateral forces are to be resisted by either shear walls or bracing systems. This dual-system approach ensures redundant load paths and enhanced seismic performance.

To comprehensively evaluate system behavior, three distinct design scenarios were investigated:

- **Case 1:** Columns resist the minimum code-required 25% of base shear (representing maximum bracing contribution)
- **Case 2:** Balanced system with columns resisting 50% of base shear
- **Case 3:** Columns resist 75% of base shear (approaching the upper limit of column-dominated behavior)

This parametric study of varying base shear distributions aligns with similar research conducted by Domínguez and Colunga, who investigated the nonlinear behavior of inverted-V and X-braced frames under Mexican code provisions. Their work demonstrated the importance of understanding force distribution between vertical and lateral load-resisting elements, particularly for different bracing configurations. The current study builds upon this foundation while specifically addressing the Indian code requirements and focusing on V-bracing systems in RC frames.

The code-compliant design approach ensures that all structural elements maintain appropriate strength and stiffness characteristics while providing valuable insights into optimal force distribution between columns and bracing systems. This methodology allows for systematic evaluation of how varying levels of base shear resistance in columns affect overall structural performance, particularly in terms of drift control, displacement demands, and energy dissipation mechanisms.

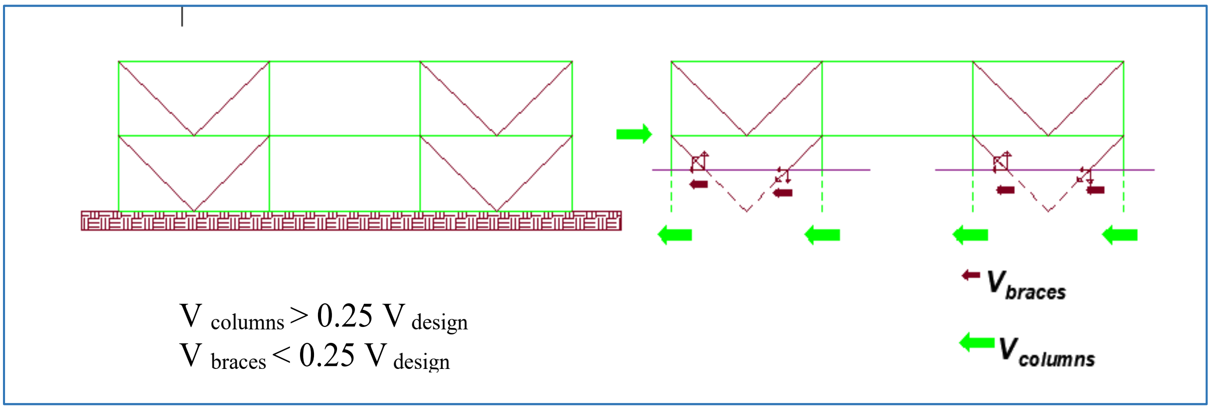


Figure 3. Base shear contribution in the columns and bracing according to the Indian standard.

## 3. Results and Discussion

The Response Spectrum Analysis (RSA) results were systematically evaluated through comprehensive comparative assessments. A detailed parametric study examined the structural performance across different base shear distribution scenarios, comparing braced and unbraced configurations. The investigation encompassed 24 structural models, comprising 12 V-braced RC frames and 12 unbraced counterparts, representing four building heights (4-, 8-, 12-, and 16-story structures) analyzed using

ETABS software. This rigorous analytical approach enabled precise quantification of the V-bracing system's influence on seismic performance metrics. For each building height category, three distinct base shear distribution cases were examined: (1) columns resisting 25% of lateral forces, (2) 50% column resistance, and (3) 75% column resistance. The unbraced frames served as control models, establishing baseline performance characteristics against which the effectiveness of the V-bracing system could be objectively measured. The comparative analysis focused on key seismic response parameters, including fundamental time period, inter-story drift ratios, lateral displacements, base shear demands, and overall structural stiffness. This multi-story investigation provided valuable insights into height-dependent performance variations and the effectiveness of V-bracing across different structural scales, from low-rise to mid-rise building configurations. The consistent modeling approach across all cases ensured reliable comparison of results, enabling clear identification of trends and correlations between bracing configurations and seismic performance enhancement.

### 3.1 The fundamental time period (FTP) of the structures

The seismic performance of structures is fundamentally influenced by their Fundamental Time Period (FTP), which serves as a critical parameter for base shear calculation and overall dynamic response [24]. The FTP is determined by several structural characteristics, including building height, structural ductility, geometric configuration, and overall dimensions. Through comprehensive software analysis of 12 braced and 12 unbraced frame models, significant variations in FTP were observed, as illustrated in Figure 4. The results demonstrate that unbraced RC frames exhibit substantially higher FTP values compared to their steel V-braced counterparts. For instance, the 4X25 model showed a dramatic FTP reduction from 0.957 sec (unbraced) to 0.425 sec (braced), representing a 44% decrease. This reduction became even more pronounced with increased base shear contributions in columns, reaching 58% and 76% reductions for X50 and X75 configurations, respectively. While FTP naturally increases with building height across all models, an inverse relationship emerged in braced frames - as column base shear contributions increased (from X25 to X75), the FTP showed a corresponding increase. This behavior contrasts with unbraced frames, where no such correlation exists, highlighting the significant stiffening effect of V-bracing systems on structural dynamics and their crucial role in modifying seismic response characteristics.

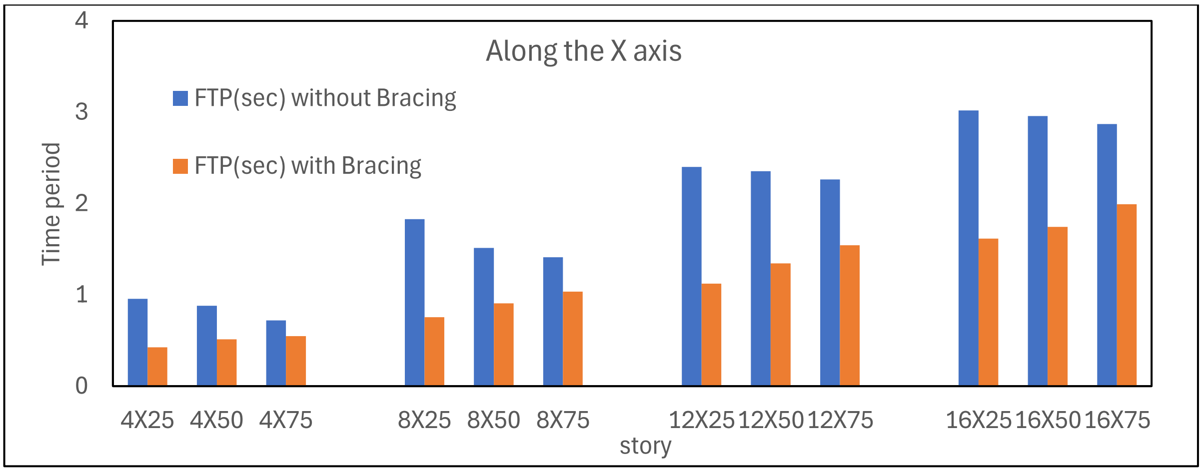


Figure 4. Fundamental Time period (FTP) of the braced and unbraced RC Frame (along the X direction).

### 3.2 Maximum story displacements and Interstory drift (ISD)

Maximum displacement and inter-story drift (ISD) serve as critical indicators of seismic performance, directly reflecting potential damage levels in structures. The comprehensive analysis demonstrates that incorporating steel V-bracing in RC frames significantly improves both parameters across all studied building heights (4-, 8-, 12-, and 16-story structures), as detailed in Tables 1-4. For 4-story buildings in the

X-direction, maximum top story displacements reduced dramatically from 25.5 mm (unbraced) to 7.1 mm (braced with 25% column base shear resistance), representing a remarkable 72% reduction. This beneficial effect, though somewhat diminished with increased column base shear contributions, remained substantial: 8-story models showed 51%, 35%, and 25% displacement reductions for 25%, 50%, and 75% column shear contributions respectively. Similar trends emerged in taller structures, with 12-story buildings achieving 44-26% reductions and 16-story buildings maintaining comparable performance benefits. The study reveals two key relationships: (1) displacement and drift reductions decrease proportionally as column base shear contributions increase (from 25% to 75%), and (2) taller structures generally exhibit greater absolute displacements while maintaining similar percentage improvements from bracing. This behavior stems from the system's force distribution - higher column shear contributions necessitate larger column sections but reduced bracing dimensions, consequently decreasing the bracing system's stiffening effect. Figure 5 clearly illustrates how ISD values escalate with both increased building height and greater column base shear participation. These patterns remain consistent in both principal directions (X and Y), demonstrating the uniform effectiveness of V-bracing in controlling structural deformations. The results conclusively establish that optimal seismic performance occurs when bracing systems assume greater portions of lateral load resistance, particularly in taller structures where drift control becomes increasingly challenging.

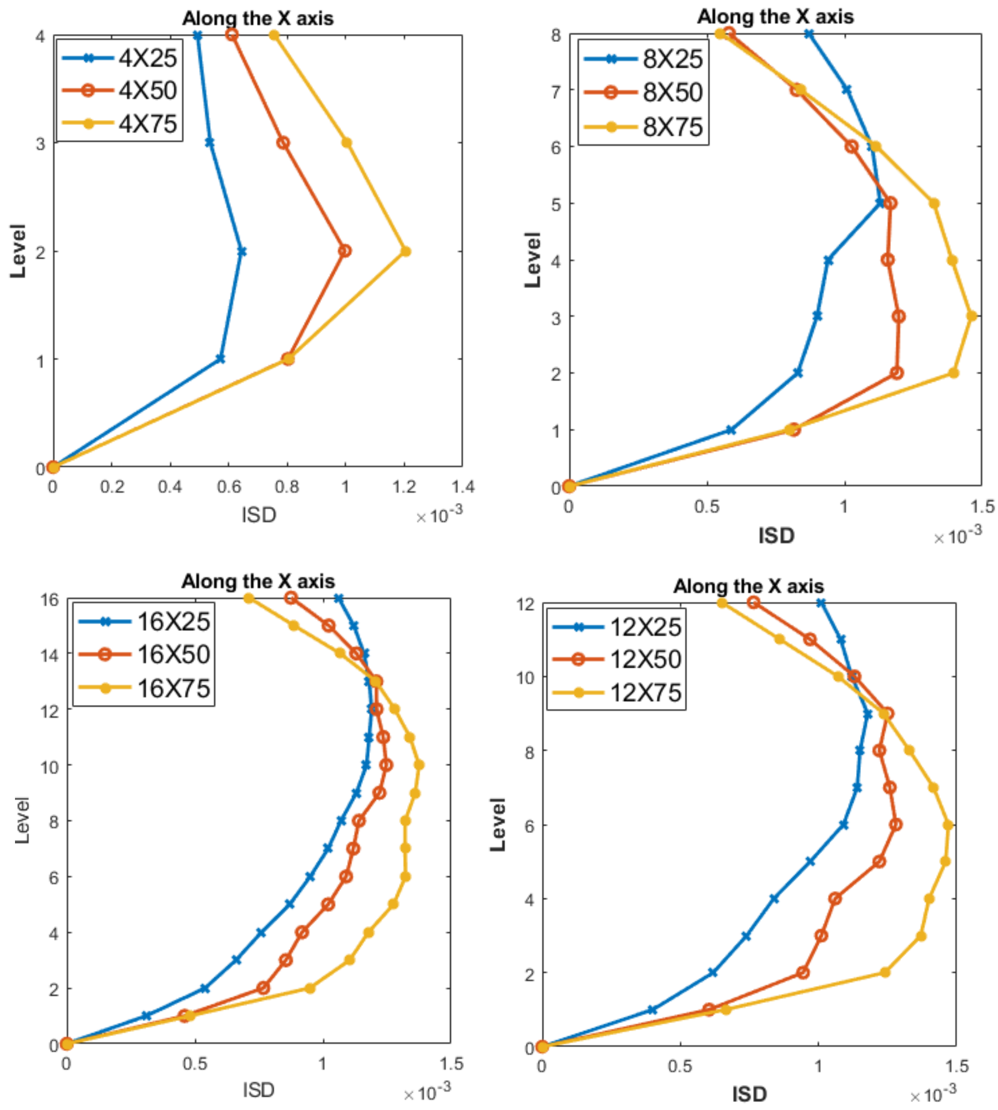


Figure 5. Inter-story drift (ISD) of the 4, 8, 12 and 16 stories with steel v-braced RC frame (along the X direction).

Table 3. Maximum Displacement and maximum stiffness of the 12 story buildings.

| **Story** | **Seismic parameter** | **lateral load contributions** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Along X axis** | | | **Along Y axis** | | |
| | | **12X25** | **12X50** | **12X75** | **12Y25** | **12Y50** | **12Y75** |
| 12 Story Structure | Max. Displacement without Bracing | 63.6 | 60.8 | 58.4 | 63.0 | 62.0 | 59.6 |
| | Max. Displacement with Bracing | 35.9 | 39.4 | 43.4 | 35.6 | 39.5 | 43.7 |
| | Disp. With bracing/without bracing (%) | 56 | 65 | 74 | 56 | 64 | 73 |
| | Max. stiffness without bracing (KN/m) | 691121.4 | 741230.6 | 968710.8 | 670898 | 719416 | 941030 |
| | Max. stiffness with bracing (KN/m) | 3422154 | 1928260 | 1634618 | 3427382 | 1915969 | 1613982 |
| | Without bracing /with bracing (%) | 20 | 38 | 59 | 20 | 38 | 58 |

Table 1. Maximum Displacement and maximum stiffness of the 4 story buildings.

| **Story** | **Seismic parameter** | **lateral load contributions** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Along X axis** | | | **Along Y axis** | | |
| | | **4X25** | **4X50** | **4X75** | **4Y25** | **4Y50** | **4Y75** |
| 4 Story Structure | Max. Displacement without Bracing (mm) | 25.5 | 23.6 | 19.8 | 25.9 | 24 | 20.2 |
| | Max. Displacement with Bracing (mm) | 7.1 | 10.1 | 12 | 7.2 | 10.2 | 12.2 |
| | Disp. With bracing/without bracing (%) | 28 | 43 | 60 | 28 | 43 | 61 |
| | Max. stiffness without bracing (KN/m) | 285938 | 360771 | 165446 | 279341 | 351996 | 158391 |
| | Max. stiffness with bracing (KN/m) | 1207515 | 870275 | 902988 | 1203292 | 863622 | 889766 |
| | Without bracing /with bracing (%) | 24 | 41 | 18 | 23 | 41 | 18 |

Table2. Maximum Displacement and maximum stiffness of the 8 story buildings.

| **Story** | **Seismic parameter** | **lateral load contributions** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Along X axis** | | | **Along Y axis** | | |
| | | **8X25** | **8X50** | **8X75** | **8Y25** | **8Y50** | **8Y75** |
| 8 Story Structure | Max. Displacement without Bracing | 47.7 | 38.9 | 37.1 | 48.4 | 39.8 | 38.1 |
| | Max. Displacement with Bracing | 23.4 | 25.1 | 27.8 | 23.3 | 25.3 | 28.2 |
| | Disp. With bracing/without bracing (%) | 49 | 65 | 75 | 48 | 63 | 74 |
| | Max. stiffness without bracing (KN/m) | 450129 | 600764.8 | 806089.8 | 438284 | 583697 | 783329 |
| | Max. stiffness with bracing (KN/m) | 2198583 | 1394415 | 1276011 | 2198138 | 1382613 | 1257501 |
| | Without bracing /with bracing (%) | 20 | 43 | 63 | 20 | 42 | 62 |

Table 4. Maximum Displacement and maximum stiffness of the 16 story buildings.

| Story | Seismic parameter | lateral load contributions | | | | | |
|---|---|---|---|---|---|---|---|
| | | Along X-axis | | | Along Y-axis | | |
| | | 16X25 | 16X50 | 16X75 | 16Y25 | 16Y50 | 16Y75 |
| 16 Story Structure | Max. Displacement without Bracing | 76.8 | 76.2 | 74.3 | 79.6 | 78.7 | 76.4 |
| | Max. Displacement with Bracing | 48.0 | 50.5 | 53.9 | 47.6 | 50.6 | 54.7 |
| | Disp. With bracing/without bracing (%) | 62 | 66 | 73 | 60 | 64 | 72 |
| | Max. stiffness without bracing (KN/m) | 896062.6 | 1015791 | 1413407 | 867771 | 983952 | 1371252 |
| | Max. stiffness with bracing (KN/m) | 4004476 | 2594199 | 2333121 | 4005284 | 2577334 | 2302751 |
| | Without bracing /with bracing (%) | 22 | 39 | 61 | 22 | 38 | 60 |

### 3.3 Base shear and maximum story stiffness

The study's comprehensive analysis reveals that implementing V-shaped steel bracing in RC frames significantly enhances two critical seismic performance parameters: base shear capacity and structural stiffness [24]. The base shear, representing the maximum lateral seismic force at a structure's base, showed remarkable improvements across all models, with the degree of enhancement depending on both building height and bracing configuration. For 4-story structures, base shear capacity increased by 30%, 24%, and 7% in models with 25%, 50%, and 75% column base shear contributions respectively. This improvement became more pronounced in taller buildings, with 8-story structures demonstrating 59%, 40%, and 26% increases, while 12- and 16-story buildings maintained substantial gains of 54-31% and 48-30% respectively. These results clearly establish that while base shear capacity naturally increases with building height due to greater mass participation, the bracing system's effectiveness progressively diminishes as column base shear contributions increase from 25% to 75%, with X25 configurations consistently delivering optimal performance.

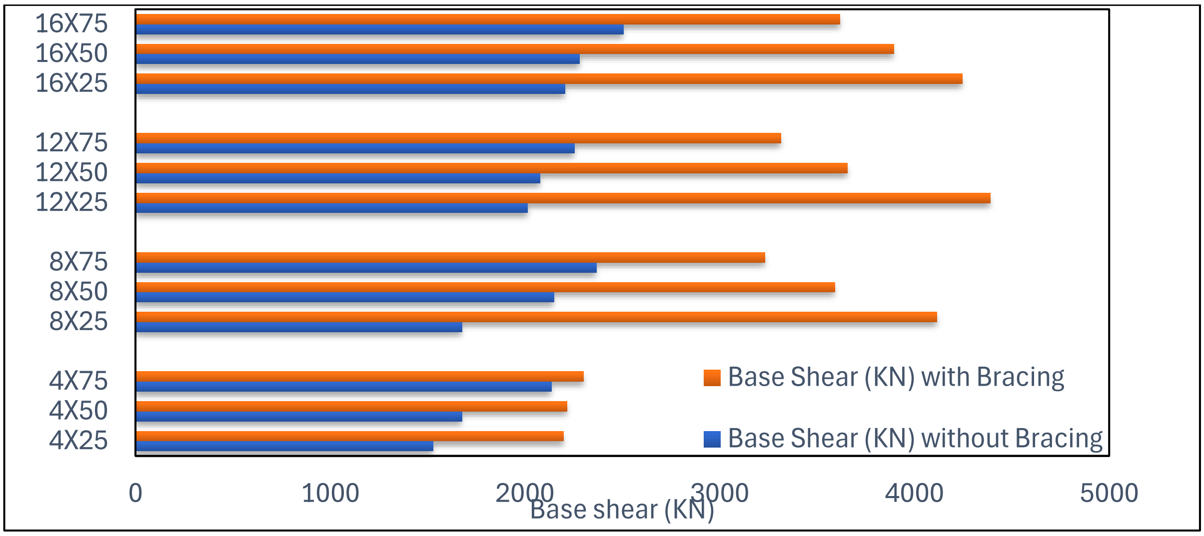


Figure 6. base shear in 4, 8, 12, and 16 stories with and without steel-braced RC frame (along X direction)

Concurrently, the addition of steel bracing substantially enhanced structural stiffness, with braced frames exhibiting 72-80% greater stiffness compared to unbraced systems when employing bracing configurations designed for 75% base shear resistance. Similar to base shear capacity, this stiffness improvement follows a predictable degradation pattern as column contributions increase. The research demonstrates that the most significant seismic performance benefits occur when bracing systems assume greater portions of lateral load resistance, with these advantages being particularly critical in taller structures where both base shear demands and drift control requirements are more substantial. Importantly, these performance patterns remained consistent in both principal directions (X and Y), confirming the reliability of V-bracing systems for multi-directional seismic resistance. The findings provide valuable practical insights for structural engineers, offering clear guidance for optimizing bracing configurations to achieve specific performance objectives while satisfying code-mandated base shear distribution requirements, ultimately leading to more resilient and cost-effective seismic design solutions.

## 3 Conclusion

The study of the effect of V-shaped steel bracing in the RC frame was discussed in the results section. After studying the behaviors of the RC frame with and without steel bracing based on story displacement, story shear, ISD, time period and base shear of the 4 to 16-story buildings, the following conclusions may be discussed:

I. The application of the steel bracing with different lateral force contributions reduced the fundamental period in all 4 to 16-story buildings. As the increased base shear capacity in the columns, the period of the models increased. The height and period of the structure are directly proportional to each other.
II. In the braced frames, the maximum top-story displacements are reduced. When the height of the structure increased, the top story displacement also increased. The base shear contribution in the columns increased, and the top story displacement also increased. Similar behaviors are observed in the inter-story drifts.
III. As the increase in height and base hear contributes to the bracing, it increases the base shear and story stiffness of the structures.

Overall, the steel bracing used in the RC frame improves the seismic capacity and reduces the inter-story and displacements of the structures. The base shear contributions in the columns (25%, 50% and 75%) increased, and their seismic behaviors also changed. In the 25% base shear contributions in the columns, these models are more likely to assume that steel is the first line of defense, whereas in the 75% base shear contribution assumed as concrete columns are the first line of defense. To understand the nonlinear behaviors of the Braced frame with the different shear contributions in the columns, a further study will be carried out with pushover analysis.

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