The Impact of Different Bracing Ratios on the Structural Performance of Planar Steel Frames

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ABSTRACT

Bracing systems are a part of steel construction projects, designed to increase stability and reduce lateral displacement. Rather than increasing the section size or reducing the span, bracing systems provide a more efficient solution. Diagonal, inverted V, X, and K bracing are the most commonly encountered configurations in practice, each of which affects structural performance differently in terms of stability and capacity. This study examines the effects of varying bracing ratios on the performance of planar steel frames using these four bracing types. Ensuring both strength and stability, especially against buckling, is critical in the design of steel structures. Using SAP2000, the buckling behavior of multi-story planar steel frames with different bracing ratios was simulated, in order to analyze the structural performance thoroughly. The results contribute to more efficient bracing arrangements that ensure safety while minimizing material usage, construction costs, and time, all without compromising aesthetics. These findings will help designers and investors optimize structural bracing for better results.

Keywords-bracing; steel structures; steel frames; stability; buckling; bracing ratio; SAP2000

I. INTRODUCTION

Reinforced concrete has been used in the construction industry for many years because of its durability and flexibility. The demand of higher, bigger and more complex structures, has led to the replacement of concrete with steel, a material known for its high strength-to-weight ratio and short construction timelines. However, steel buildings are susceptible to corrosion, have poor fire resistance, and are instable. A significant number of strategies are proposed in order to resolve the structural instability of steel constructions [1-6], such as reducing the span, increasing the cross-sectional area and integrating bracing systems, with the last one being the most effective method. Bracing systems provide additional stiffness, reduce lateral displacement, and improve the overall load-bearing capacity of structures from winds and seismic incidents [7]. This is why they are used in steel-frame structures, from low height buildings to high towers. Some of the most common types of bracing systems are: diagonal bracing, X-bracing, inverted V-bracing., and K-bracing, with different effects on structures, focusing on lateral displacement reduction, material efficiency, and buckling resistance. Authors in [8] identified the bracing systems that minimize material usage while maintaining structural integrity, while authors in [9, 10] used structural analysis software, like ETABS and STAAD.Pro, to optimize the performance of high steel structures under different bracings. Additionally, authors in [11] utilized ABAQUS software to examine the influence of bracing length and configuration on the stability of steel structures. Authors in [12] conducted a comparative analysis to determine the bracing systems that provide the highest buckling resistance. Different types of bracing have been extensively examined, but there is a significant gap in the research on the impact of varying bracing ratios within a single structure. Bracing ratio, being the proportion of the frame that is braced relative to the total number of available bracing positions, can affect both the stability and efficiency of a structure. Measuring the bracing ratio can optimize the usage of materials and reduce the cost of bracing. The objective of this study is to examine the effects of varying bracing ratios on the structural performance of flat steel frames for the four common bracing systems: diagonal, X, inverted V, and K. SAP2000 structural analysis software, was used to provide a complete evaluation of how different bracing ratios affect key structural performance metrics. The findings of the research provide practical insights for structural engineers and designers, leading more efficient, cost-effective, and safe steel structures. Furthermore, the study proposes better practices in bracing system design, ensuring that both stability and material efficiency are optimized without reducing the aesthetics and economic viability of the structure.

II. CASE STUDY OF A FIFTEEN-STORY PLANAR STEEL FRAME

In this study, a fifteen-story planar steel frame was evaluated to determine the effect of varying bracing ratios on its structural performance. Linear buckling analysis was conducted using SAP2000 V24 to ascertain critical structural metrics, including the buckling coefficient, story shear, and self-weight of the frame. The linear buckling method is important for calculating the critical load based on the buckling coefficient, which is derived from the first buckling mode. Authors in [13] proposed the finite element formulation of beam-column elements, while the geometrical configuration and loading conditions for the planar steel frame are detailed in Table I. The frame under test consists of 15 floors, with each floor having a typical height of 3.8 meters. The structure comprises four bays, with each bay measuring 5 meters. The design of the steel frame is: beams ISBM550, columns ISBM300, and braces ISBM100. The structure is subjected to a load of 60 kN/m, with joint forces distributed from the bottom to the top. The load distribution, as shown in Table I, exhibits variation across different joints, commencing at 33 kN at the base and progressively increasing to 54 kN at the top, thereby ensuring realistic loading conditions for the analysis. Four types of bracing systems were examined in this study: diagonal, X, inverted V, and K bracing. These bracing systems were installed at varying ratios, ranging from 20% to 100% of the frame area, as presented in Figures 1-8. The bracing ratios were selected to explore the progressive influence of additional bracing on structural stability, buckling behavior, and overall efficiency. The abbreviations for each bracing system and their installation ranges are depicted in Table II.

TABLE I. GEOMETRY AND LOADING OF STEEL FRAME

Parameter	Type/ Value
Number of stories	15
Typical story height	3.8 m
Number of bays	4
Bay width	5 m
Beam size	ISBM550
Column size	ISBM300
Brace size	ISBM100
Frame loads	60 kN/m
Joint loads on the left from bottom to top	33, 37, 40, 42, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54 (kN)

The frame's buckling analysis was conducted using SAP2000 V24 and the linear analysis was performed to determine the buckling coefficient for each bracing type at different bracing ratios. The buckling coefficient, which is indicative of the structure's resistance to instability under axial loads, was calculated from the first buckling mode. The analysis also focused on determining the story shear forces and self-weight of the steel frame for each bracing configuration. These metrics offer insight into the stiffness of the frame and the effectiveness of each bracing system in minimizing lateral displacements under loads.

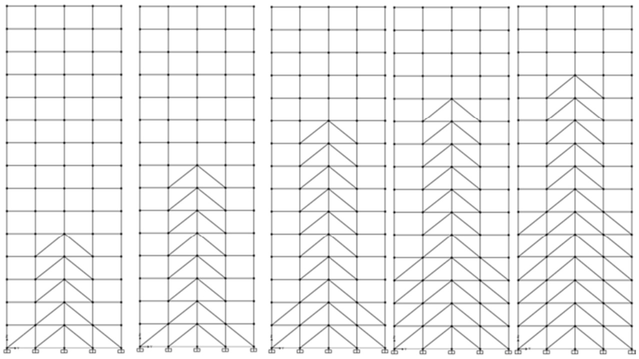

Fig. 1. Diagonal brace accounts for 20%-60% of the frame area.

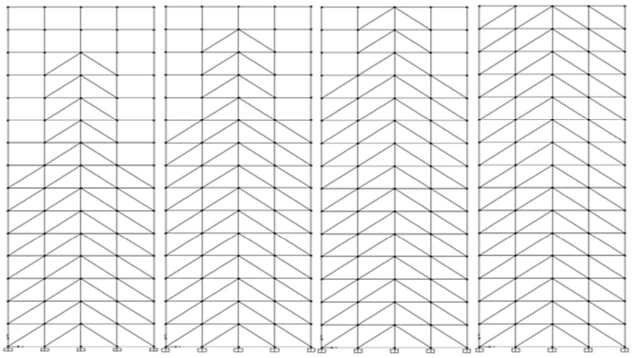

Fig. 2. Diagonal brace accounts for 70%-100% of the frame area.

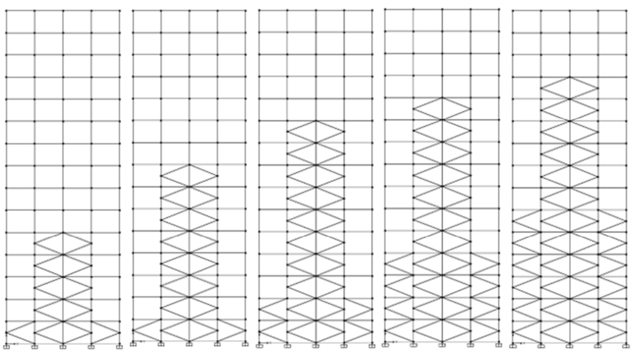

Fig. 3. K brace accounts for 20%-60% of the frame area.

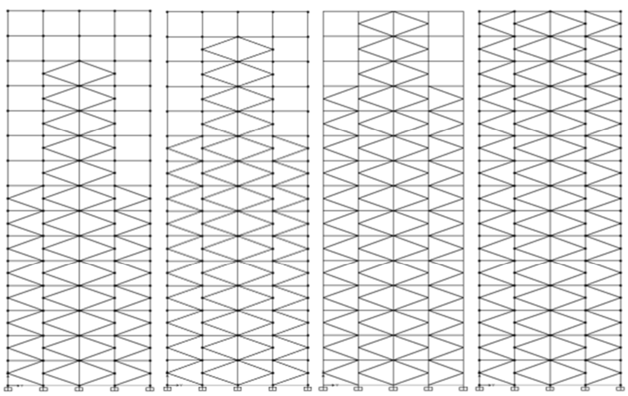

Fig. 4. K brace accounts for 70% to 100% of the frame area.

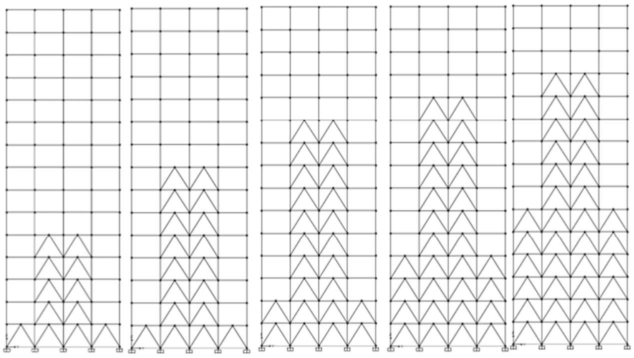

Fig. 5. Inverted V brace accounts for 20%-60% of the frame area.

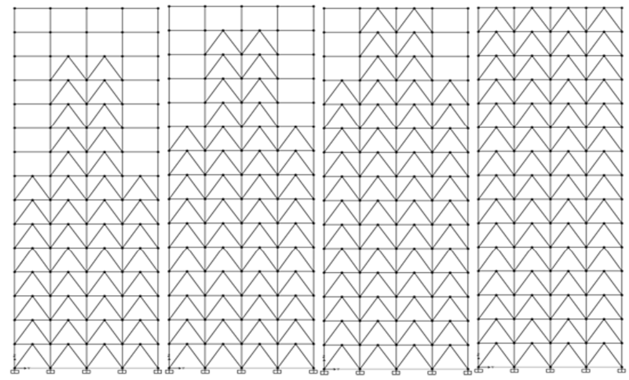

Fig. 6. Inverted V brace accounts for 70%-100% of the frame area.

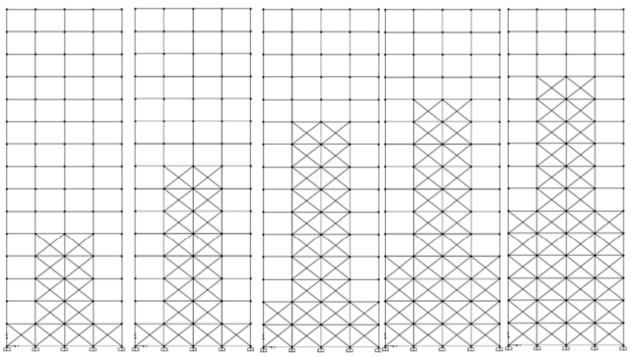

Fig. 7. X brace accounts for 20%-60% of the frame area.

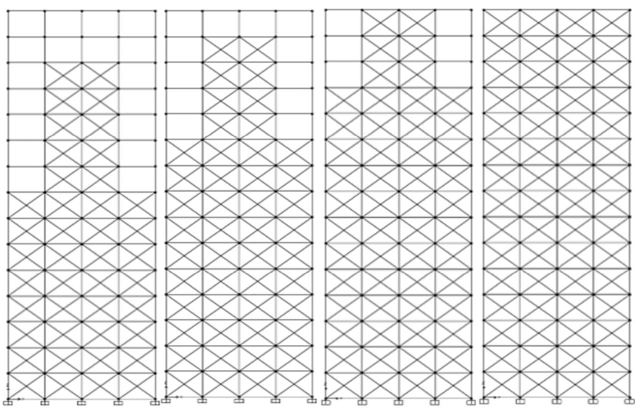

Fig. 8. X brace accounts for 70%-100% of the frame area.

TABLE II. FIGURES' GUIDE

Bracing system	Abbreviation
Diagonal bracing	D
X bracing	X
Inverted V bracing	iV
K bracing	K

III. RESULTS AND DISCUSSION

The findings of this study reveal the significant effect of bracing ratios on the structural performance of planar steel frames for four common bracing systems: diagonal, X, inverted V, and K bracing. The analysis, performed using SAP2000 V24, focused on the buckling coefficient, self-weight, and story shear of the frames under varying bracing ratios. The buckling coefficient, a significant indicator of structural stability, was found to increase with the bracing ratio for all bracing types, as depicted in Table III. Among the various bracing systems evaluated, X bracing consistently exhibited the highest buckling values, demonstrating superior stability under axial loads, especially at higher bracing ratios. In contrast, K bracing exhibited the lowest buckling values, suggesting reduced stability compared to other configurations. Inverted V bracing demonstrated higher buckling values than diagonal bracing across all ratios, indicating superior performance in mitigating buckling. These findings disclosed that X-bracing is the most effective in improving the structural stability of planar steel frames, especially when a high bracing ratio is used.

TABLE III. VALUES OF BUCKLING COEFFICIENT WITH VARIOUS BRACING RATIOS

Bracing ratio	Buckling coefficient			
	K bracing	Diagonal bracing	Inverted V bracing	X bracing
100%	14.73	18.12	20.95	23.16
90%	14.72	18.10	20.89	23.06
80%	14.59	17.86	20.36	22.26
70%	13.84	16.28	17.84	18.54
60%	11.84	12.71	12.99	13.04
50%	9.59	9.76	9.84	9.85
40%	7.81	7.85	7.89	7.89
30%	5.62	5.62	5.63	5.64
20%	3.95	3.95	3.95	3.95

It is noteworthy that while the buckling coefficient increased with the bracing ratio, the rate of improvement diminished beyond a certain point. For instance, between 80% and 100% bracing ratios, the increase in the buckling coefficient was negligible. Conversely, at lower bracing ratios (20%-50%), as shown in Figure 9, the differences in buckling performance among the various bracing types were less pronounced. This observation indicates that the selection of bracing type becomes particularly critical at higher bracing ratios, while at lower ratios other factors, such as material efficiency and construction cost, may play a more decisive role. An analysis of the self-weight of the steel frames displayed in Table IV, revealed that X bracing, while demonstrating the highest buckling performance, also resulted in the greatest self-weight, as presented in Figure 10. This is a significant factor, as the additional weight can result in increased material costs and foundation requirements. Despite its comparatively lower buckling performance, K bracing was found to be only slightly lighter than X bracing, raising questions about its cost-effectiveness. Diagonal and inverted V bracings exhibited a more balanced performance, with moderate self-weight and good stability, being preferable alternatives in cases where weight is a limiting factor.

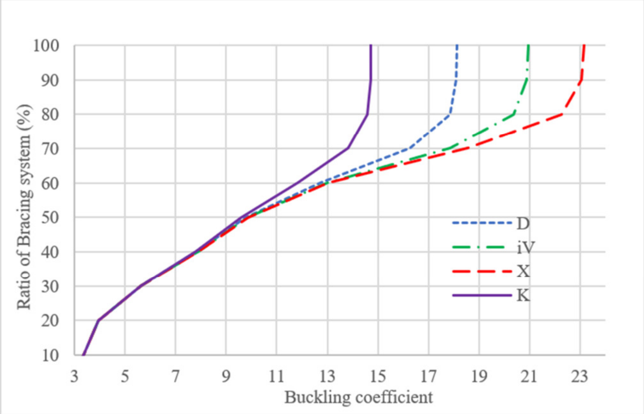

Fig. 9. Variation of the buckling coefficient according to the bracing ratio.

TABLE IV. SELF-WEIGHT OF STEEL FRAME

Bracing ratio	Self Weight (kN)			
	Diagonal bracing	Inverted V bracing	K bracing	X bracing
100%	461.55	476.38	484.80	494.62
90%	458.24	471.59	479.18	488.00
80%	454.94	466.80	473.54	481.39
70%	451.63	462.01	467.91	474.78
60%	448.32	457.22	462.28	468.16
50%	445.02	452.43	456.65	461.55
40%	441.71	447.64	451.02	454.94
30%	438.40	442.86	445.38	448.32
20%	435.10	438.07	439.75	441.71

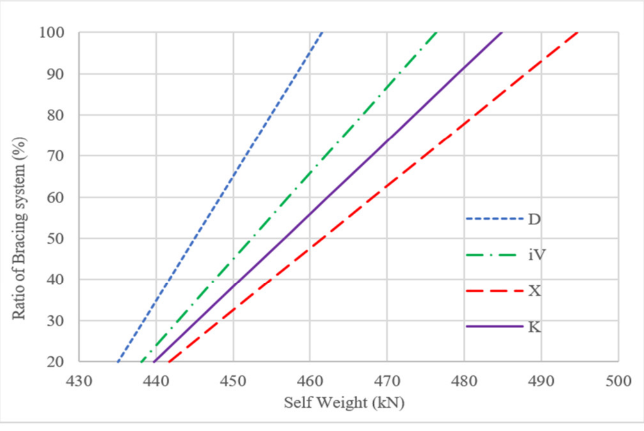

Fig. 10. The relationship between self-weight and bracing ratio.

The story shear analysis presented in Figures 11-19 shows that the inverted V bracing resulted in the lowest story shear at the base (story 1), indicating its effectiveness in reducing lateral displacements. This behavior was consistent for most of the bracing ratios. Similar to the buckling behavior, the absolute values of story shear for X bracing were consistently higher than those for diagonal and K bracing. However, at bracing ratios of 40% and 50%, the differences in story shear between bracing types were negligible, underscoring the importance of selecting the appropriate bracing configuration based on specific design requirements, rather than shear performance alone. The apparent difference in story shear from 60% to 100% is evidenced in Figures 15-19.

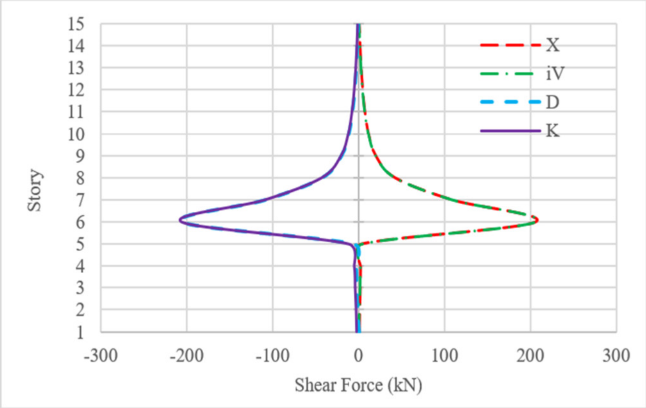

Fig. 11. Value of story shear when the bracing ratio is 20%.

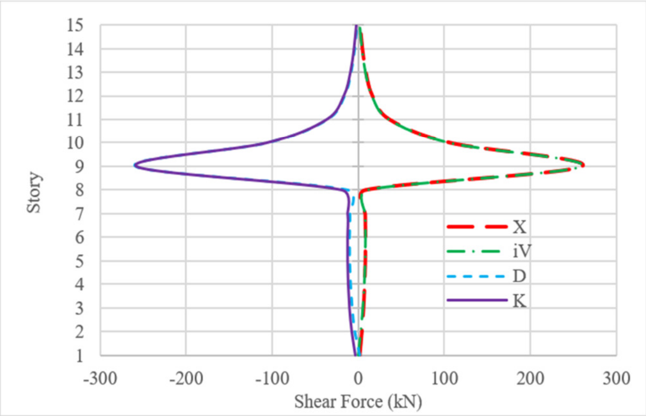

Fig. 12. Value of story shear when the bracing ratio is 30%.

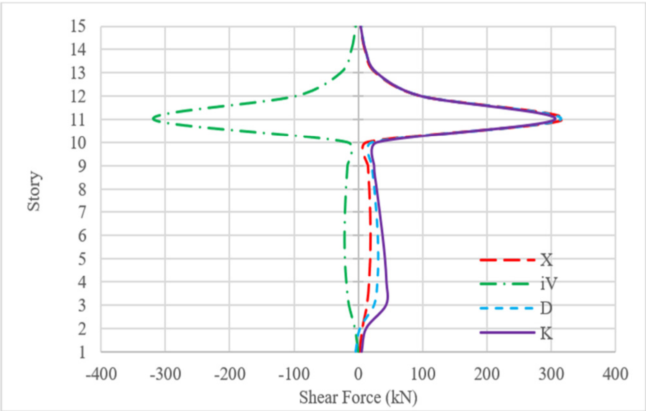

Fig. 13. Value of story shear when the bracing ratio is 40%.

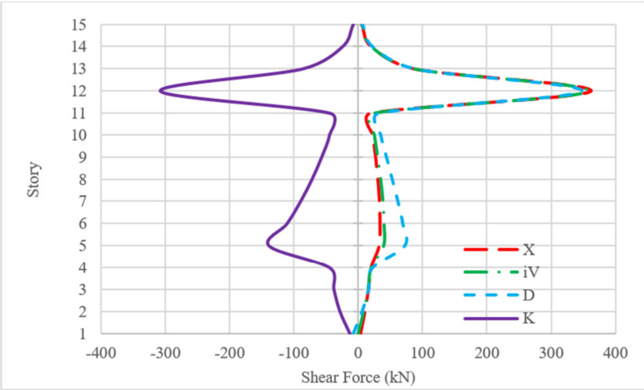

Fig. 14. Value of story shear when the bracing ratio is 50%.

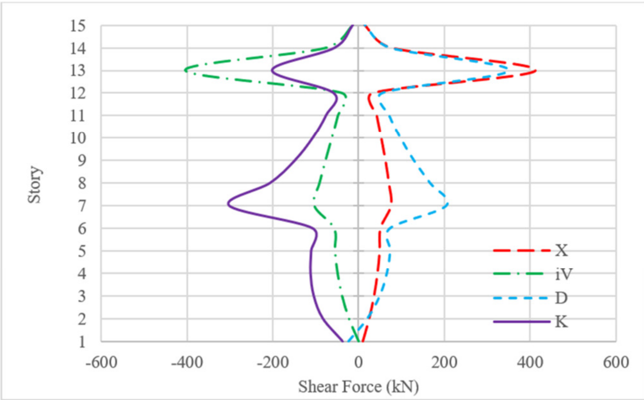

Fig. 15. Value of story shear when the bracing ratio is 60%.

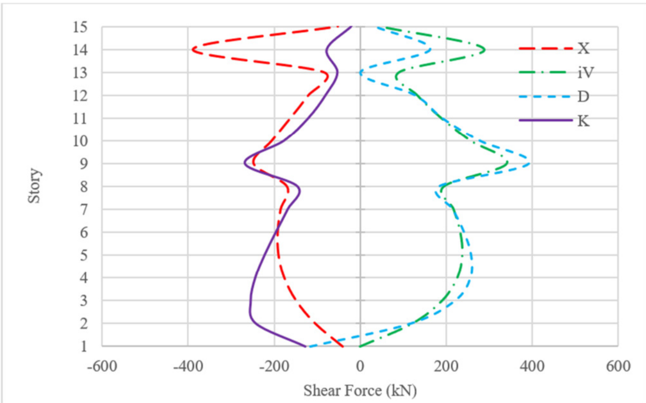

Fig. 16. Value of story shear when the bracing ratio is 70%.

The findings of this study are in agreement with the existing literature, confirming that increased bracing ratios improve frame stiffness and stability. However, the findings also indicate a decline in effectiveness at higher bracing ratios, suggesting that beyond a certain point, the benefits of increased bracing are outweighed by the added material costs and construction complexity. This study offers novel insights by linking the bracing ratio to both buckling and story shear performance, providing a more holistic perspective on optimizing bracing systems for steel structures.

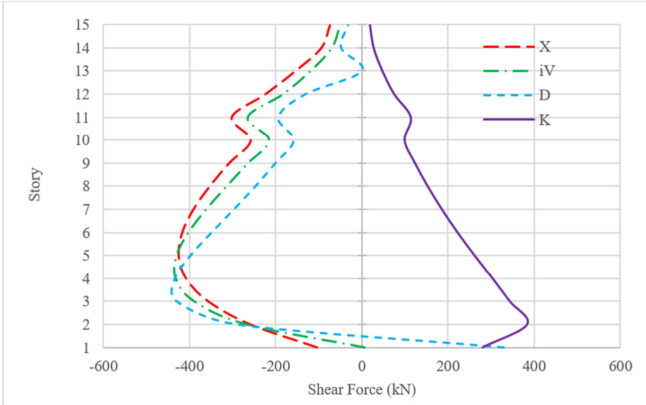

Fig. 17. Value of story shear when the bracing ratio is 80%.

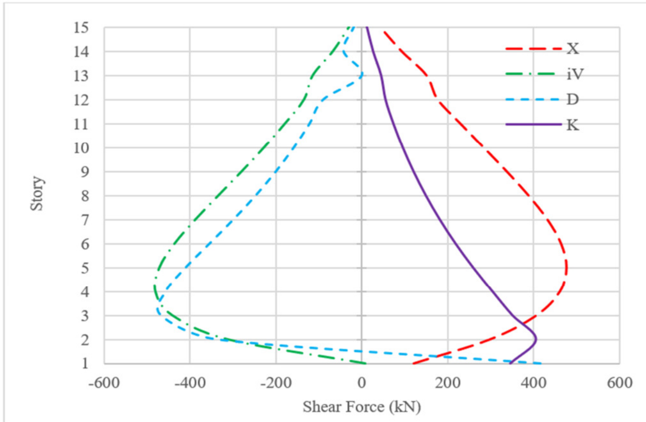

Fig. 18. Value of story shear when the bracing ratio is 90%.

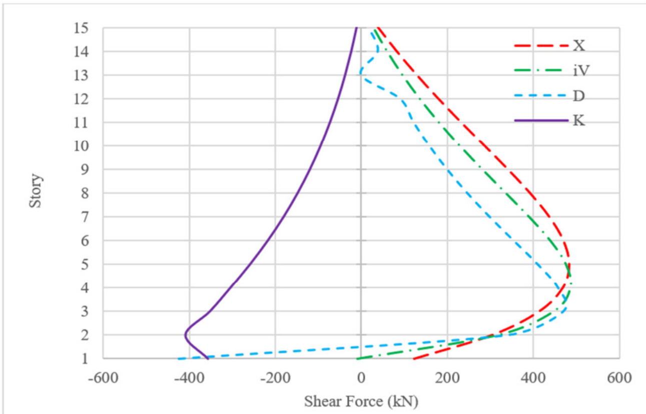

Fig. 19. Value of story shear when bracing ratio is 100%.

IV. CONCLUSIONS

This study examines the structural performance of planar steel frames equipped with four different bracing systems—diagonal, X, inverted V, and K bracing—under varying bracing ratios. The results of the study provide evidence that the bracing ratio plays a critical role in determining the stability, weight, and lateral performance of steel frames. The key findings are:

- X bracing has demonstrated superior performance in terms of its resistance to buckling, when employed in higher bracing ratios. This makes X bracing the most suitable option for applications where ensuring structural stability is of the utmost importance.
- K bracing exhibits the least stability and is, therefore, not recommended in cases where high buckling performance is required, despite its marginal weight advantage over X bracing.
- Inverted V bracing is a balanced solution, offering lower story shear and good buckling performance while maintaining a relatively low self-weight, making it a suitable choice for designs where lateral displacement control is crucial.
- The study demonstrates that increasing the bracing ratio beyond 80% provides diminishing returns in terms of stability improvement. Conversely, at lower bracing ratios (20%-50%), the differences in performance among the bracing systems are less significant, suggesting that material and cost considerations may take higher priority in these cases.
- The selection of bracing type should not be made solely on the basis of buckling performance; factors such as self-weight, story shear, and material costs, must also be considered to optimize the design of steel frames.

This study highlights that the effectiveness of bracing in enhancing structural stability is not only determined by the type of bracing, but also by the appropriate bracing ratio. The bracing ratio plays a critical role in meeting structural, aesthetic, and economic demands, while optimizing construction time. The integration of this study's findings into design processes is intended to help designers take better decisions, rather than relying on an arbitrary selection of bracing types without considering their ratios. These insights are highly relevant to practical design and construction. Furthermore, the outcomes of this simulation-based research serve as a foundational basis for validating advanced analysis and design software in the field of structural and civil engineering.

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