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Comparative Analysis on Structural Behaviour of Steel Structure Using Different Types of Bracing Due to Dynamic Earthquake Loads

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ABSTRACT

Earthquake-resistant steel structures must have adequate strength and serviceability to withstand and distribute seismic forces throughout the structure. The structure should not be too stiff or too ductile. High structural stiffness causes small deformations in the structure and affects the absorption of seismic energy. On the other hand, structures that are too flexible can cause deformations beyond the structural limits. One effective approach to enhance earthquake resistance in high-rise buildings is the incorporation of lateral bracing. This study outlines a numerical simulation of a five-story steel building, employing various bracing types using specialized software. The objective is to assess the structural behavior of the building both with and without bracing, specifically analyzing three configurations: V-bracing, inverted V-bracing, and two-story X-bracing. Key aspects of the structural behavior examined include natural periods, internal forces, inter-story drift, and overall stiffness. All models maintain consistent dimensions for structural elements, loading conditions, and the placement of bracing, positioned in the building's weak direction. A dynamic analysis was conducted utilizing the response spectrum method. The findings reveal that structures equipped with inverted V-bracing and two-story X-bracing exhibit superior performance compared to those with V-bracing, while the V-bracing still offers enhancements over structures lacking any bracing.

1. Introduction

Indonesia frequently experiences earthquakes caused by tectonic and volcanic activities. High-magnitude earthquakes pose a risk of infrastructure damage. Seismic forces can induce structural failure and, in some cases, trigger progressive collapse, where initial localized failures propagate and result in partial or complete structural failure. Buildings that are inadequately designed to withstand seismic loads are particularly dangerous, threatening the safety of occupants [1]. Therefore, building structures must be designed to be strong enough to withstand all the loads, including lateral loads due to earthquakes.

Ductile materials play an important role in seismic design, as they allow structures to undergo longer inelastic deformation phase before collapse when subjected to loads beyond their elastic limits, preventing dangerous sudden collapse. Steel material has high compressive, tensile and ductility strength so it is widely used in earthquake-resistant structural systems. In addition, one of the most important aspects of structural performance is lateral stiffness, which affects the structure's ability to resist displacement due to lateral loads. Lateral stiffness also significantly affects the natural period of the structure [2]. In practice, steel structures can be strengthened using various methods to resist lateral forces generated by earthquakes. To increase the stiffness of a building structure, lateral reinforcement, or additional bracing system, can be used within the structural system [3].

The primary function of structural reinforcement, or bracing, is to act as a support to resist lateral forces caused by earthquakes. Reinforcement is most effective when installed at the weak axis of a structure; structural

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reinforcement can significantly improve a building's stability and stiffness. The use of structural bracing can reduce the maximum floor displacement compared to unbraced structures. Furthermore, displacement tends to decrease progressively from the upper to the lower floors of the building [4]. Structural strengthening through bracing in steel buildings increases the overall strength of the structure against lateral loads and reduce earthquake effects [5].

There are two main types of bracing systems commonly implemented in steel structures: concentric bracing and eccentric bracing. Eccentric bracing offers better structural performance than concentric bracing in terms of deflection and moment capacity. However, this advantage is influenced by the level of eccentricity when bracing systems with eccentricities exceeds 20% tend to experience a decrease in both deflection control and moment capacity control [6]. Numerous studies have been conducted on concentric bracing systems, and various bracing configurations have been shown to improve the structural performance of tall buildings under dynamic loading. The selection of structural system and bracing type has a significant influence on the overall structural response. Several types of concentric bracing such as diagonal bracing, X-bracing, and combinations of these configurations can increase the seismic resistance of buildings. Among all of them, combined bracing systems tend to show superior performance in terms of structural response [7]. X-type steel bracing significantly increases structural stiffness and reduces maximum inter-story drift in the structural frame. This bracing system not only increases the lateral stiffness and strength capacity, but also increases the displacement capacity of the structure [8]. However in other studies, diagonal reinforcement was shown to provide superior structural performance in terms of lateral deflection, support reaction, and bending moment when compared to type X reinforcement [9].

Despite existing research, there is still considerable scope for further research into the characteristics and configurations of different bracing systems to identify the most optimal reinforcement strategy. Therefore, this study analyzes and compares the structural performance of different reinforcement configurations, namely V-bracing, inverted-V bracing, and two-story X-bracing. These configurations were selected due to their similar geometric characterstics. In particular, the two-story X-bracing resembles the inverted-V bracing on the first floor and the V-bracing on the higher floors as presented in Figure 5.

The objective of this study is to compare the structural behavior of a five-story steel building by examining several different types of concentric bracing, they are V-bracing, inverted V-bracing, and two-story X-bracing. The structural behavior that analyzed includes natural period, inter-story drift, deflection, structural stiffness, and internal forces in the structure. This study is particularly relevant to local conditions in earthquake-prone areas of Indonesia. By incorporating regional seismic characteristics and specific structural requirements of the area, the findings are expecteded to make a significant contribution to the advancement of structural engineering practices, particularly in in the development of buildings with adequate strength and resistance to loads, especially lateral loads specifically dynamic earthquake activity. The building structure plan evaluated in this study is presented in Figure 1.

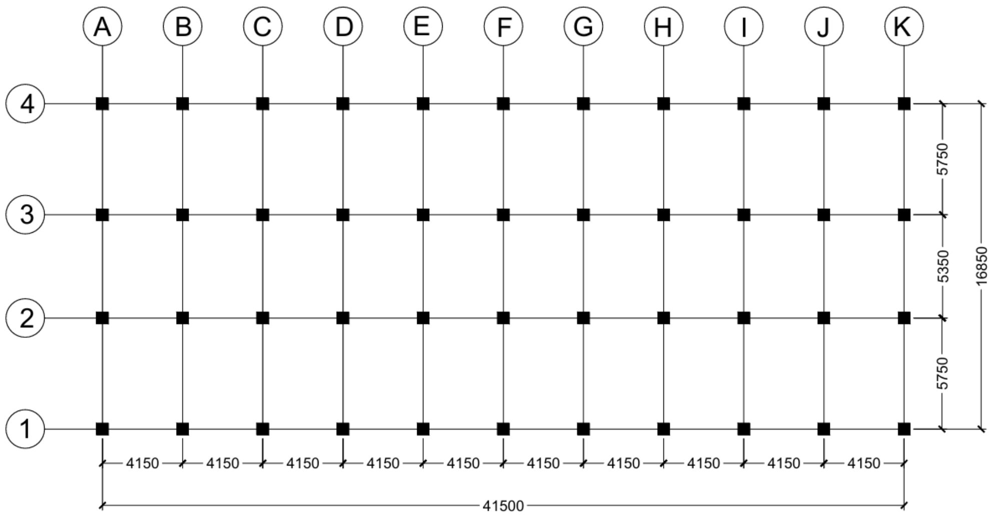

Figure 1. Building plan

2. Methods

This study was conducted through numerical modeling using finite element-based structural analysis software. The modeled structure is a three-dimensional steel building incorporating several bracing variations. A structure without bracing was used as a control model for comparison. All structural models have typical configurations, including geometry, dimensions of structural component and the loading conditions. The bracing is placed at the same location in the building plan along the weak axis of the structure, as illustrated in Figure 2. The modeled structure is a five-story steel building located in Bandung, Indonesia.

Figure 2 presents a typical floor plan of the modeled building structure. Steel bracing is an effective solution for resisting lateral loads and can be designed to resist either partial or full seismic loads. Bracing placement also plays a significant role in determining the overall structural strength, therefore, the weak axis of the building must be carefully evaluated. In addition, the location of bracing at different heights in the structure affects the resistance and stiffness characteristics, leading to variations in the structural response [10].

Bracing or other forms of strengthening, when properly positioned, can significantly enhance structural stability. Improvements in structural performance are due to the reduction in the distance between the center of mass and the center of stiffness, which helps optimize structural behavior under lateral loads. [11]. Figure 2 illustrates the bracing configurations applied to the building, where the bracing is located along the weak direction of the structure. These configurations are referred to as A-frame and K-frame systems. The corresponding building frame models for each bracing variation are shown in Figure 3, Figure 4, and Figure 5.

The analysis was performed using the linear dynamic analysis method. his approach allows the identification of structural weaknesses, which can then be considered in selecting appropriate bracing systems. Furthermore, more multiple bracing configuration may be used to address structural weaknesses observed structural displacement due to lateral forces [12]. Linear dynamic analysis was used to evaluate the torsional effects, displacements, structural stiffness, and to determine the seismic response based on the structural modes. Structural stiffness is influenced by several factors, including the dimensions, geometry, and lengths of columns and bracing members.

The torsional irregularity ratio provides important information regarding the potential for structural damage under earthquake loading. The magnitude of the torque effect increases with the number of stories. Both deformation and displacement must be carefully controlled in structural design. Deformations exceeding permissible and non structural components of the building [13].

This study adheres to the following Indonesian standards: SNI 1727-2013, wich specifies the minimum design loads for building and other structures; SNI 1729-2020, wich provides specifications for structural steel buildings; and SNI 1726-2019, which outlines procedures for the earthquake-resistant design of buildings and non-building structures. The objective of this research is to examine the effects of various bracing configurations on the behavior of steel structures, using the same loads and dimensions for all modeling variations.

The dynamic earthquake load used in the modeling is the response spectrum (Figure 6), orresponding to the building location, as specified in SNI 1726-2019.

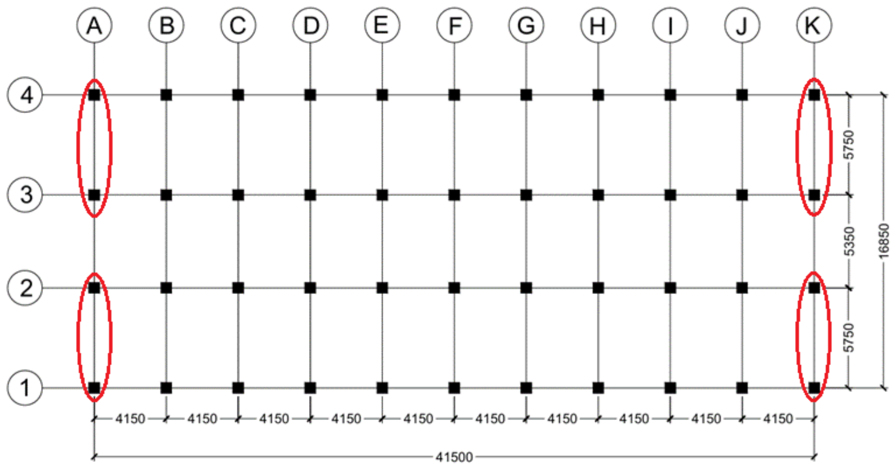

Figure 2. Building plan configuration with bracing

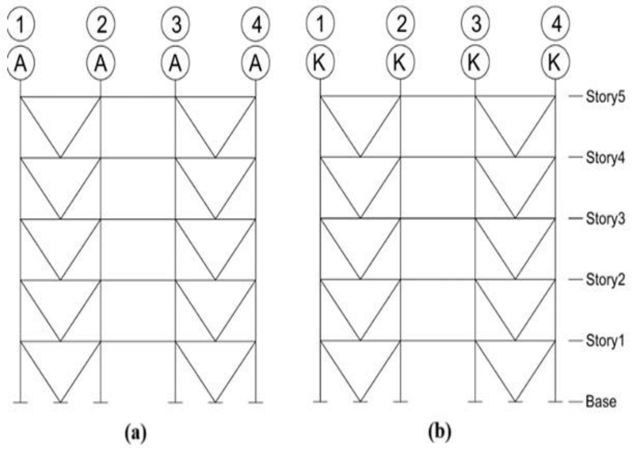

Figure 3. Frame configuration with V-bracing : (a) A portal (b); K portal

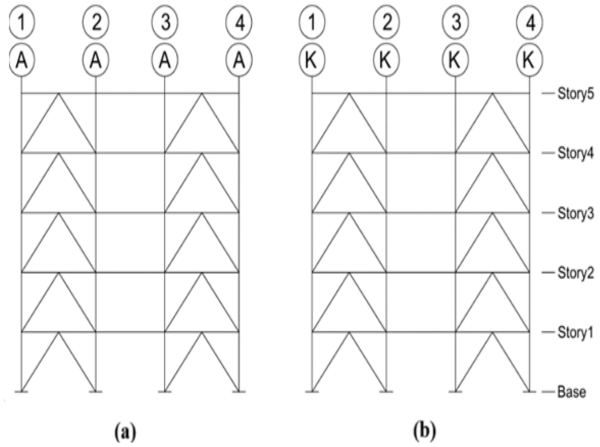

Figure 4. Frame configuration with inverted V-bracing : (a) A portal (b); K portal

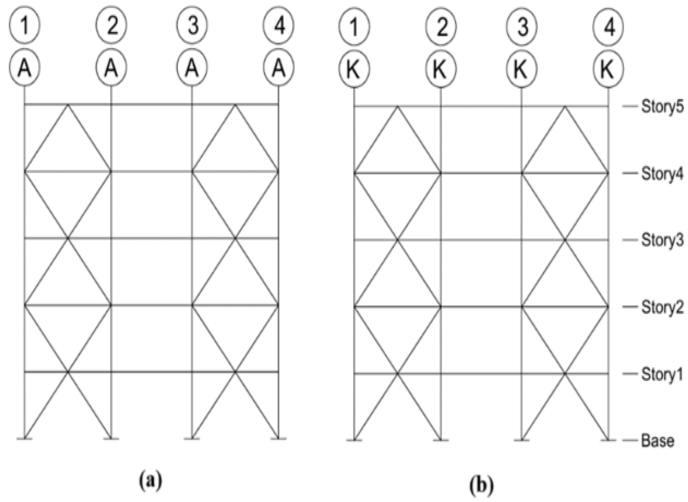

Figure 5. Frame configuration with two-story X-bracing : (a) A portal (b); K portal

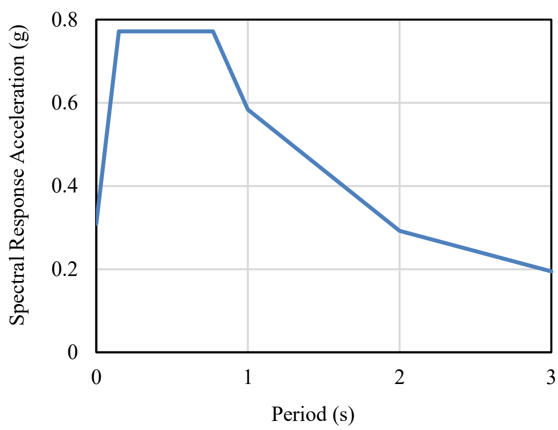

Figure 6. Design earthquake response spectrum at Bandung

3. Results and Discussion

This study shows significant influence of bracing configuration on the seismic performance of steel structures. The inverted V-bracing and two-story X-bracing systems improves structural behavior by reducing displacements, inter-story drift, and structural periods. Strengthening the structure by installing bracing increases stability and strength in resisting seismic loads. Among all the bracing variations analyzed, inverted V-bracing and the two-story X-bracing showed superior structural stiffness in terms of smaller displacements, and better torsional resistance. These findings are consistent with previous studies that identify inverted V-bracing as an efficient solution for enhancing the lateral load resistance of structures. Although the two-story X-bracing also demonstrates good structural behavior, the inverted V-bracing configuration provides the most effective structural behavior in terms of strength and stiffness.

This study focuses on the importance of selecting an appropriate bracing system based on the structural characteristics of the building and applied seismic loads. While V-bracing has better structural performance than the building structure without bracing, however, still smaller than the inverted V bracing and two-story X bracing, particularly in minimizing lateral displacement and increasing structural stiffness.

Steel bracing systems enhance the seismic capacity of mid-rise buildings by increasing stiffness, reducing inter-story shifts, and improving structural stability. Therefore, the selection of an optimal bracing system is crucial in the earthquake-prone regions such as Indonesia. This study was conducted by modeling the building structure with earthquake loading in accordance with SNI 1726-2019, providing insights tailored to the seismic conditions at the building's location. Two-story inverted V-shaped and X-shaped bracing are recommended for mid-rise steel structures in earthquake-prone areas, offering an effective balance between performance and material efficiency.

3.1. Period and Internal Forces

The results of the modal analysis indicate that all model variations exhibit a dominant first mode shape in the translation direction, especially along the X-axis. This behavior is attributed to the relatively regular horizontal plan of the building, which minimizes the rotational effects. The mode shape analysis shows that, for all variations, translational displacement in the X direction is the most prominent, indicating the main deformation mode under lateral loading. Accordingly, the first structural mode shape for all modeling variations is dominated by the translational direction. This behavior is due to the relatively regular structural plan in the horizontal direction, which minimizes rotational effects Table 1 presents the mode shapes for each modeling variation, confirming the dominance of translational motion in the X direction..

The largest translational displacement, equal to 0.0014, occurs in the unsupported structure in the X direction, whereas the smallest displacement, 0.0003, is observed in both the inverted V-braced and two-story X-braced configuration. The V-braced variation exhibits a displacement of 0.0007. In the second mode shape, translation in the Y direction remains dominant, however, a slight rotational component is present in all modeling variations. The smallest rotation value, 8.9×10^{-7}, is recorded for the two-story X-braced configuration, indicating that this configuration provides the most effective torsional resistance.

The torsional response, as observed from the rotational component of the mode shapes, is lowest in the two-story X-braced model. This finding is particularly important, as torsional irregularities can result to unexpected stress concentrations and damage during seismic events, especially in asymmetric or irregular structures. The addition of symmetrical and strategically placed bracing not only enhances stiffness but also improves the uniformity of the structural response, thereby reducing torsional amplification. Moreover, bracing placement in the weak direction (the Y-axis in this study) substantially increases stiffness and balances the stiffness distribution across axes. This balanced behavior reduces the risk of plan irregularities, which are often penalized in modern seismic design codes due to their poor performance observed in past earthquakes.

Table 1. Mode shape

Variation	Mode Shape	UX	UY	RZ
Without Bracing	1	0.7952	0.0014	0
	2	0.0016	0.7698	2.57E-06
	3	0	2.14E-06	0.7881
Two story X bracing	1	0.7957	0.0003	0
	2	0.0001	0.7763	8.90E-07
	3	0.1158	3.90E-05	5.58E-06
V bracing	1	0.7942	0.0007	0
	2	0.0003	0.8153	3.51E-06
	3	0	2.63E-06	0.8518
Inverted V bracing	1	0.7961	0.0003	0
	2	0.0001	0.7825	2.26E-06
	3	0.1159	2.77E-05	2.87E-06

Table 2. Participating mass ratio

Variation	Participating Mass Ratios					
	Sum UX	Mode	Sum UY	Mode	Sum RZ	Mode
Without bracing	0.9118	4	0.9019	5	0.9054	6
Two story X bracing	0.9116	3	0.9008	6	0.9378	9
V bracing	0.9098	4	0.9235	5	0.9708	9
Inverted V bracing	0.9121	3	0.9029	6	0.9396	9

The implementation of a bracing system significantly reduces structural displacement, especially in the two-story inverted V-bracing and X-bracing configurations, which exhibit the smallest displacement value. This result shows that these bracing configurations significantly enhance the lateral stability of the building.

Regarding the mass participation ratio (Table 2), wich is a crucial factor in dynamic analysis, all variations—including the braced structures— had a high mass participation ratio that satisfy the requirements specified in SNI 1726-2019. This indicates that these modeling variations adequately captured the building's dynamic behavior, with the combined mass participation exceeding the minimum threshold of 90%. The dominant structural response can be observed from the mass participation factor for each mode shape, where the mode with the highest mass participation factor represents the most significant response. Among the braced models, the two-story inverted V-bracing and X-bracing configurations exhibited relatively better dynamic behavior, as evidenced by the shorter period values and higher mass participation ratios.

The reduction in structural period observed in the braced structures aligns with the general principle that the addition of bracing increases overall structural stiffness. A shorter structural period indicates that the building can return to its original position more quickly after lateral displacement, thereby improving its ability to withstand seismic loads. The structural period represent the time required for a structure to return to its original shape after being subjected to a lateral load. Consequently, the use of bracing results in a reduced period, reflecting increased structural rigidity.

In the first mode shape, representing the initial structural response to seismic loading, the story shear force decreases as the story height increases due to the cumulative load in the direction of gravity. Figure 7 and Figure 8 display the story shear forces in the X-axis and Y-axis directions, respectively. Both figures show closely aligned lines for all modeling variations, indicating that there are no significant difference in story shear force among the variations. Meanwhile, the base shear force, resulting from the dynamic earthquake load response spectrum is summarized in Table 3. The base shear force in the X and Y directions varies between the inverted V-bracing and two-story X-bracing variations. However, similar to the story shear force, the base shear force values do not differ significantly across all modeling variations.

Table 3. Structural Period

Variation	Period (Sec)
Without bracing	1.020
Two story X bracing	1.003
V bracing	1.011
Inverted V bracing	1.004

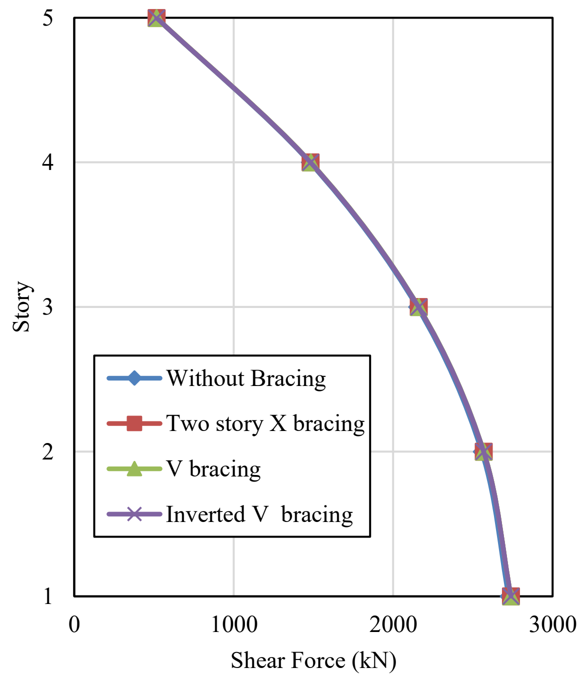

Figure 7. Shear story in X-direction

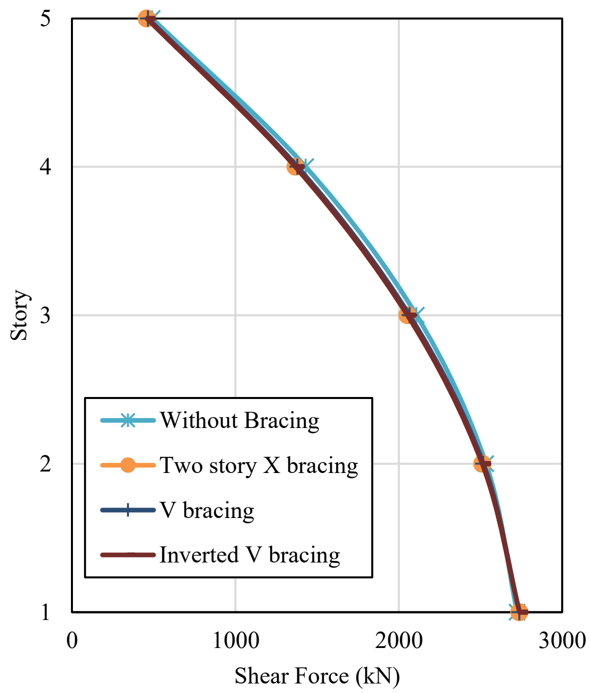

Figure 8. Shear story in y direction

The first mode period of the structure without bracing has the largest period value compared to the structures with bracing. However, the period value does not exceed the maximum period required for a five-story building. The shortest structural period, 1.003 seconds, is observed in the two-story X-bracing variation, while the inverted V-bracing configuration has a slightly longer period of 1.004 seconds; this difference is negligible. According to SNI 1726-2019 on Earthquake Resistance in Buildings and Non-Building Structures, the dynamic base shear force must exceed the static base shear force in both the X-axis and Y-axis directions. Therefore, verification of this requirement is essential. The results of this study confirm that, for all modeling variations, the dynamic base shear force exceeds 100% of the static base shear force. The result of base shear in X and Y direction summarized in Table 4.

Table 4. Base shear

Variation	Base Shear X-dir (kN)	Base Shear Y-dir (kN)
Without bracing	2,724.5598	2,724.5604
Two story X bracing	2,736.8807	2,754.6048
V bracing	2,739.3269	2,739.3231
Inverted V bracing	2,736.6439	2,754.9828

Figure 9 and Figure 10 present comparisons of axial forces and maximum bending moments obtained from the same structural element in each modeling variation. The largest axial force, equal to 2,840.355 kN, occurs in the unbraced structural model, whereas the smallest maximum axial force is observed in the structure model with inverted V-bracing. The comparison of maximum bending moments follows a similar pattern to that of the axial forces. The largest maximum bending moment occurs in the structure model without bracing, while the smallest maximum bending moment, 283.948 kN, is found in the inverted V-bracing variation.

The axial force in the bracing also vary among the different configuration. The axial force for the V-bracing is 637.599 kN, while values of 713.808 kN and 788.849 kN are observed for the inverted V-bracing and two-story X-bracing systems, respectively. These differences in axial forces arise from the structural conditions, which maintain the same reinforcement dimensions for all variations. Therefore, the dimensions of the steel profiles for V- bracing and inverted V-bracing can be optimized to achieve a more economical design.

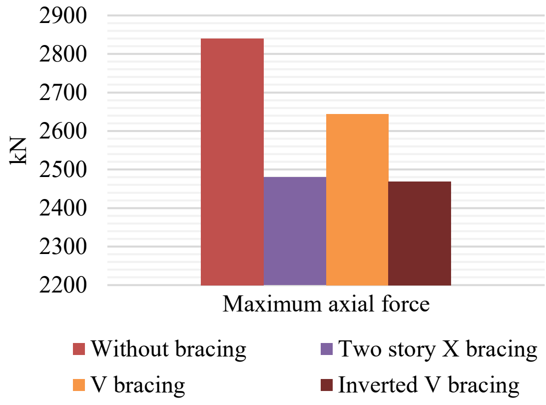

Figure 9. Axial force maximum

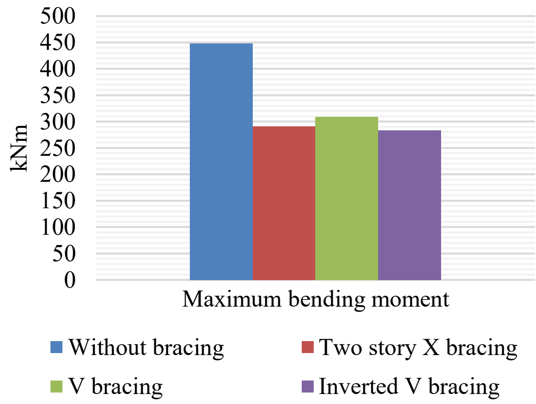

Figure 10. Bending moment maximum

Steel bracing is an effective method to increase the strength of structural frames. The bracing system reduce bending moments and shear forces in the structure, thereby minimizing floor displacement and shifting [14]. However, the two-story X-bracing structural model exhibits maximum axial forces and bending moments that are similar to those of the inverted V-bracing model. Nevertheless, the inverted V-bracing system demonstrates better structural performance compared to the V-bracing configuration [15].

Bracing system function by modifying the load distribution, especially lateral loads to the foundation. In an unbraced frame structures, lateral loads are resisted solely by beams and columns ; as a result, the internal forces and displacements are greater than those in braced frame systems. The result of this study confrim that the largest axial forces and bending moments occur in the structural system without bracing, which indicates high loads on each structural component. In contrast, a braced frame takes some of the lateral loads through axial forces in the braces, making the system more efficient. The two-story X-bracing and inverted V-bracing system exhibited the lowest axial forces and bending moments in the primary frame elements. The maximum bending moment in the unbraced structure model was nearly double the maximum bending moment observed in the inverted V-bracing structure model. This finding confirms the effectiveness of inverted V-bracing in reducing excessive stresses in beams and columns and enhancing the overall strength of the structure against lateral loads. Furthermore, this reduction in internal forces allows for the potential to downsizing the dimensions of the primary frame and resulting in more economical design.

3.2. Story Drift and Displacement

Inter-story drift refers to the relative lateral displacement between two building stories, while story displacement is the lateral displacement of a specific story which measured from the base level of the building. According to SNI 03-1726-2019, the inter-story drift is a critical parameter for maintaining structural stability and preventing damage to non-structural components; therefore, it must not exceed the prescribed limit values. The bracing systems in all models effectively control lateral displacement, preventing excessive deformation of the building due to earthquake loading. Figure 11 shows that the inter-story drift values for all structural variations, in both the X- and Y-axis directions, remain within the allowable limits.

The results show that the inter-story drift in V-bracing is greater than the inter-story dirft in the inverted V-bracing and in two-story X-bracing structure. The inverted V-bracing and two-story X-bracing have similar behavior which are produce the smallest inter-story drift among all structural models considered. Meanwhile, the displacement in X direction is nearly typical for all variations, as illustrated in Figure 12 and Figure 13.

The more difference is observed in the Y direction which the unbraced structure has larger displacement compared to all the braced models (see Figure 14 and Figure 15). It shows that bracing significantly control lateral displacement of structure. Furthermore, the V-bracing experiences larger structural displacement than both the inverted V-bracing and two-story X-bracing systems. Further analysis shows that the unbraced model has higher displacments specifically in the Y direction, while the bracing systems show better performance. This finding in line with previous studies that suggest the inverted V bracing improve structural stability and torsional resistance under lateral loads. The results underline the importance of selecting an appropriate bracing configuration to enhance the seismic performance of structural buildings.

The inverted V-bracing and two-story X-bracing configurations show no significant difference in structural displacement which both exhibited the smallest displacements compared to the other models. The inverted V-bracing demonstrates better results in the structural period and displacement compared to the regular V-bracing. The steel bracing is effective system in reducing torsional effects, mitigating buckling, and reducing shear loads in beams and columns by transferring lateral loads through axial load mechanisms [16].

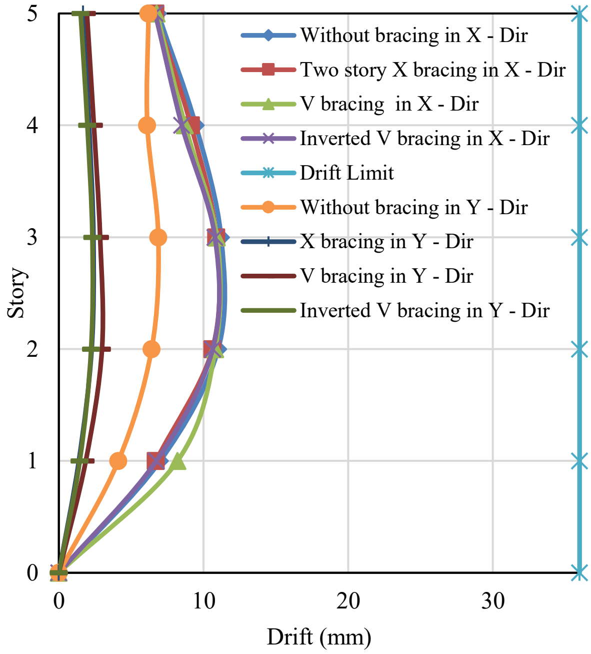

Figure 11. Inter-story Drift

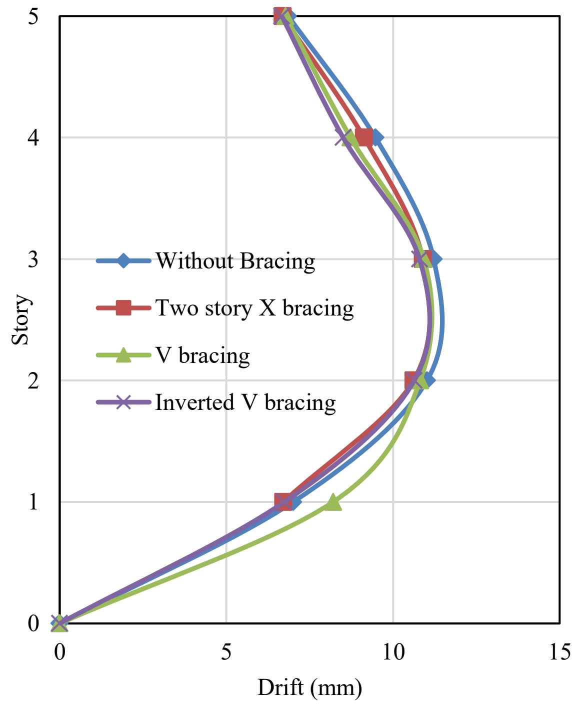

Figure 12. Inter-story drift in x direction

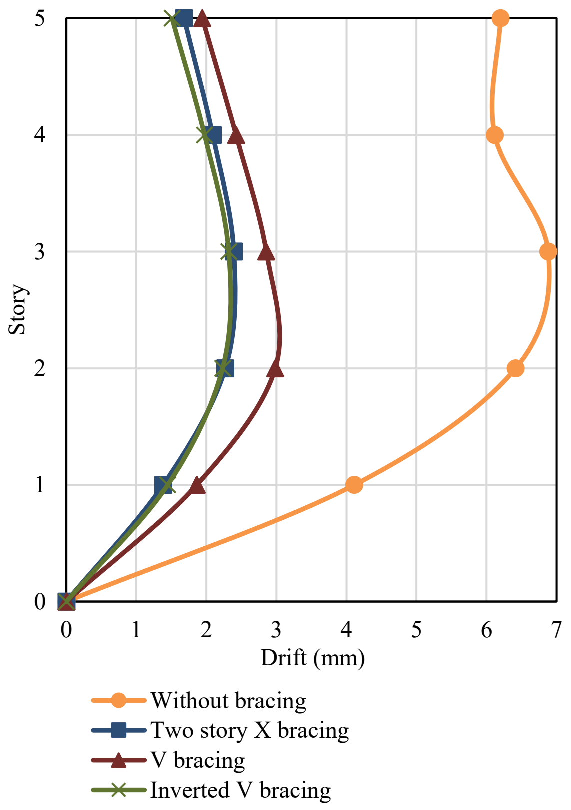

Figure 13. Story drift in y direction

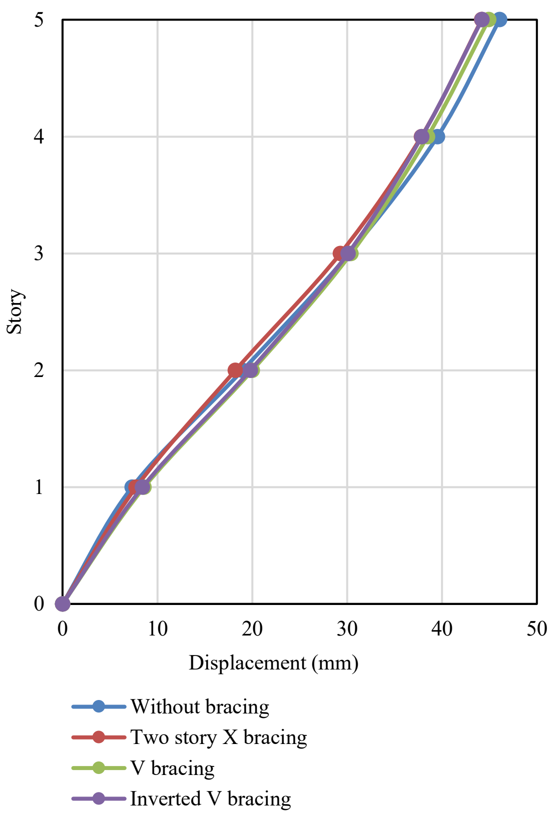

Figure 14. Displacement in x direction

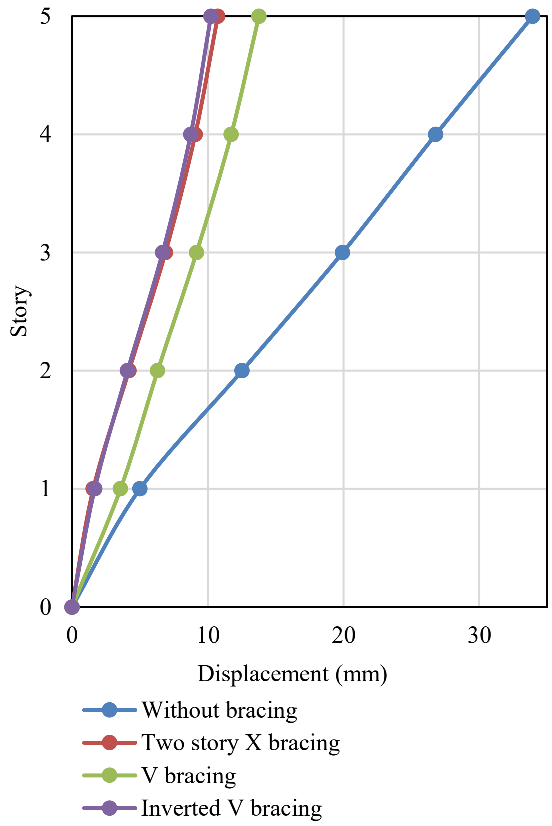

Figure 15. Displacement in y direction

3.2. Stiffness

The stiffness analysis provides valuable insights to improve structural performance in resist lateral loads. The story stiffness decreases as the number of stories increases, which is mainly attributed to the decreasing axial load in columns at the upper story levels. The structure model without bracing exhibits the smallest stiffness values, which indicates that the building is more susceptible to lateral displacements and has lower resistance to lateral forces.

Story stiffness decreases as the number of stories increases because the load carried by the columns in the upper stories is less than the load carried by the columns in the lower stories. Figure 16 shows the stiffness in the X direction, which is the strong axis of the building. There is no significant difference in stiffness along the X-axis. Overall, the unbraced structural model shows the smallest stiffness value compared to the other models. However, as seen in Figure 16, the stiffness of the first floor in the V-bracing structure is smaller than that of the structure model without bracing. On the second floor, the stiffness of the structural model with V bracing increases compared to the structure model without bracing.

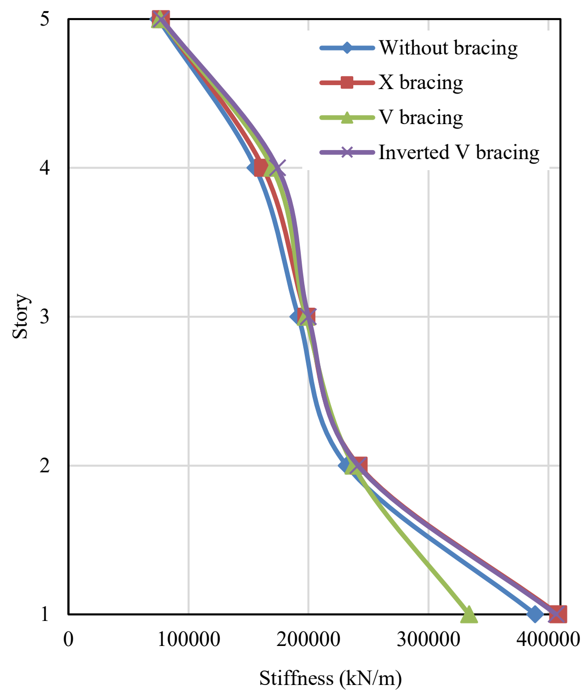

Figure 16. Stiffness in x direction

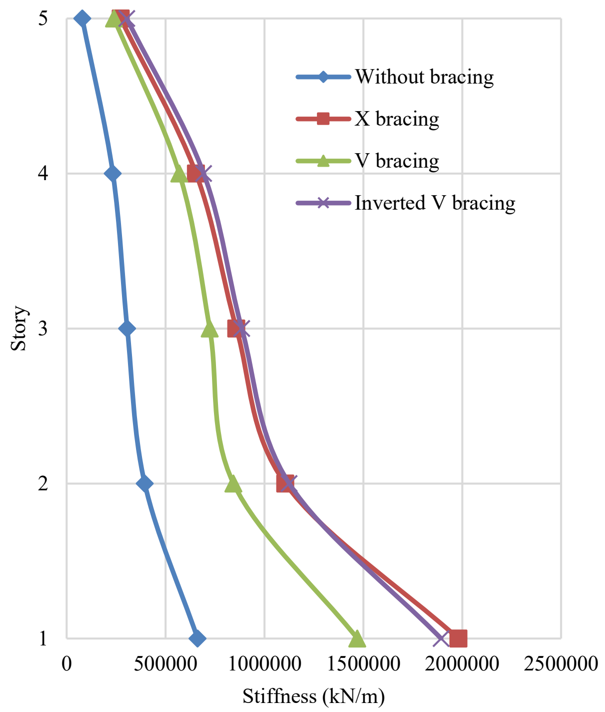

Figure 17. Stiffness in y direction

Meanwhile, the stiffness in the Y direction as shown in Figure 17, which is the weak axis, the stiffness values show a clear difference. The stiffness of the structural models without bracing is smaller than that of the other models. Structural models with inverted V-bracing and two-story X-bracing have stiffness values that are similar to each other, and both exhibit greater stiffness compared to the V bracing model. This finding aligns with previous research comparing V-bracing and inverted V-bracing, where the inverted V-bracing model demonstrated the best structural response in terms of strength and stiffness. The inverted V-bracing model is efficient in resisting lateral loads induced by dynamic earthquake forces [17]. Overall, steel bracing can increase seismic capacity, structural stiffness and ductility. While the story drift and the structural period decreases due to the dynamic earthquake loads [18].

4. Conclusions

Buildings reinforced with inverted V-bracing and two-story X-bracing reinforcement exhibit better structural behavior compared to those with V-bracing. However, the structural behavior of V-bracing buildings is still superior to that of buildings without bracing. Structural behavior encompasses the structural period, story shear force, maximum axial force, maximum bending moment, drift, displacement, and structural stiffness. The longest first mode shape period is observed in the structure model without bracing, while the shortest period is found in the models with inverted V-bracing and two-story X-bracing variations. The inverted V-bracing and two story X-shaped bracing significantly increases structural stiffness, making it more effective in resisting lateral loads caused by dynamic seismic action. Although all bracing configuration improve structural performance compared to the unbraced model, variations in axial forces between bracings indicate indicate opportunities for optimizing material utilization. The inverted V-shaped and two stroy X-shaped supports can benefit from cross-sectional optimization of the bracing members. This finding opens up the potential for further research on cost-effective amplifier configurations using performance-based design or nonlinear time history analysis for more accurate predictions of structural behavior under seismic loading.

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