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Structural Performance Optimization of Multi-Story Steel Frames with Split-K EBF Bracing System Configuration

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Bracing,
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ABSTRACT

Conventional steel frame structures tend to be susceptible to earthquakes, which can lead to significant economic and social losses. The earthquake disaster has motivated various technological exploration efforts to improve the seismic resilience of building structures. To strengthen the structure and prevent collapse, reducing the span length by adding bracing to the weak axis of the column proved effective. The addition of lateral stiffeners (bracing) to the elements of the frame structure is crucial in reducing lateral forces due to earthquakes in high-rise buildings. However, the researchers only focused on comparing the types of bracing used. Therefore, the purpose of this study is to optimize the structure of the steel frame multi-story building by innovating the configuration of bracing placement to match the composition of the building. To produce optimal results, the steel frame building model using bracing is varied in the placement of bracing with the middle model (BC1), the edge model (BC2), and the even model (BC3), so that the three models produce the effect of bracing placement on the building. The three building models will be analyzed using SAP200 to produce the performance of the steel frame building structure, including displacement, natural vibration periods, and base shear forces. From the overall analysis of the three models, it is shown that the evenness model (BC3) produces the most optimal structural performance. This is also shown by the fulfillment of all structural performance requirements based on the requirements of earthquake-resistant structures in SNI 1726-2019. The result of the buffer evenly provides a large displacement that occurs on the 3rd floor in the X direction which compared to other models has the smallest value, which is 20.13 mm. Based on the results of the analysis, it is known that the uniform model has the smallest natural vibration period value of 0.779 seconds in the X direction and has the largest dynamic shear force value in the X direction, which is 4,823.74 kN. Therefore, it can be concluded that there is an effect of the placement of supports in steel frame multi-story buildings on the ability of the building structure with the even placement model (BC3) to produce the most optimal building design when compared to other building models.

1. Introduction

Conventional steel frame structures tend to be susceptible to earthquakes, which can lead to significant economic and social losses. Earthquake disasters have motivated various technological exploration efforts to improve the seismic resilience of building structures [1][2]. One of the innovative solutions is the use of light steel healthy instant house, which utilizes strap brace panel walls and light steel materials to increase resistance to lateral forces [3][4]. To strengthen the structure and prevent collapse, reducing the span length by adding bracing to the weak axis of the column proved effective. The addition of lateral stiffeners (bracing) to the elements of the frame structure is crucial in reducing lateral forces due to earthquakes in high-rise buildings. This bracing structure system consists of two general types, namely the Concentric Braced Frame System (SRBK) and the Eccentric Bracing Frame System (SRBE), where the SRBE can absorb lateral loads effectively through links that produce inelastic rotation in structural deformation [5]. Thus, the use of bracing not only strengthens the structure but also accelerates the dynamic response of the building during an earthquake, providing better protection from potential damage or

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collapse. The use of eccentric bracing in this system has proven to be very effective because it can efficiently absorb lateral forces and increase the capacity of inelastic deformation, thereby reducing the risk of collapse due to large earthquake loads [6].

Challenges in seismic performance arising from the interaction between civil structures and earthquakes in highly seismic regions have prompted extensive research, primarily focused on lateral stability. Over recent decades, this concern has driven seismic and structural engineering researchers to develop various structural systems designed to exhibit adequate seismic performance under diverse ground motions. These systems are expected to provide sufficient stiffness to maintain elastic behavior, minimizing lateral displacement to protect non-structural elements during minor to moderate earthquakes. Additionally, they must prevent collapse during major earthquakes by accommodating structural damage, allowing for inelastic behavior in such scenarios [7]. One structural system, which is recognized for its high lateral stiffness and its capacity to dissipate large amounts of energy and to provide good inelastic capacity under cyclic loads, is the eccentrically braced frame (EBF) [7].

Recent research trends emphasize the development of resilient infrastructure designed to enhance safety, robustness, and durability while maintaining acceptable performance levels under various disaster scenarios, including fire exposure. This approach aims to create systems capable of withstanding extreme conditions without significant loss of functionality, ensuring structural integrity and minimizing recovery efforts post-disaster. Researchers are exploring advanced materials, innovative design methodologies, and performance-based evaluation techniques to achieve infrastructure that not only resists initial impacts but also facilitates rapid recovery and long-term sustainability [8][9][10][11]. Progressive collapse is a key factor in evaluating the resiliency of high-rise buildings, especially essential infrastructure. It involves the cascading failure of structural elements, often caused by the loss of a critical component, leading to partial or total collapse. Analyzing progressive collapse is complex, as it requires accounting for nonlinear dynamic responses, inelastic behavior, large deformations, and potential instabilities. Significant progress in modeling techniques over the years has improved simulations of progressive collapse under extreme events like blasts, earthquakes, and impacts, enhancing strategies for designing more resilient buildings [11][12][13].

A study by Mahenz [14], experiments on the split-K capacity of EBF against link length variations showed that link length affected displacement. The test piece with a long link variation had a maximum displacement of 42.16 mm, while the test piece with a short link had a smaller maximum displacement, which was 28.2 mm. These results show that the longer the link, the greater the displacement value generated. A study by Wijaya and Rochmah [15], a comparison of displacement results in V-Braced and Split K-Braced bracing structures, with smaller displacement results occurring in structures using the Split K-Braced bracing type with a displacement value in the X direction of 24.03 mm and the Y direction of 24.19 mm.

This research's main goal is to optimize the structure of steel frame multi-story buildings by innovating the configuration of bracing placement to match the composition of the building. The optimal plan is to have the best value in structural performance including building displacement, vibration periods, and base shear forces. Based on previous research conducted by Mahenz [14], there has been no direct test regarding the application of the Split-K EBF (Eccentric Braced Frames) design with variations in the placement of bracing in multi-story buildings with steel frame structures. Therefore, this research needs to be carried out with numerical analysis. Thus, the purpose of this study is to determine the effect of bracing placement on steel frame multi-story buildings and find the optimal configuration that can produce an efficient building structure and meet the requirements of multi-story buildings.

2. Methods

2.1. Eccentrically Braced Frame (EBF)

EBF structural system is a combination of the Moment Resisting Frame (MRF) and Concentrically Braced Frame (CBF) structural systems. This is due to the limited inelastic behavior occuring in the beam link, while the other elements of the stucture remains elastic during the seismic load. Therefore, the EBF structural system can provide high ductility such as MRF system and can also provide high elastic stiffness such as CBF system [16][17]. The links beam in EBF behaves as a short beam with shear forces acting in opposite directions at both ends so that the resulting moments at both ends of the beam have the same magnitude and direction. During the seismic load, the links beam will undergo inelastic rotation while other components of the EBF remain elastic, and finally the links beam becomes active and start yielding [18].

EBFs are widely employed as an effective seismic load-resisting system, particularly in building structures. This innovative system utilizes the yielding of a horizontal link beam situated between eccentric braces to absorb seismic energy, offering both ductility and significant energy dissipation capacity under earthquake loading conditions. Extensive research has been conducted to evaluate the performance of EBFs in various configurations, demonstrating their reliability and adaptability in achieving seismic resilience. These studies highlight the critical role of the link beam in controlling inelastic deformation and ensuring the system's stability during dynamic events [19][20][21][22][23][24].

2.2. Materials

Steel Frame Buildings are a type of building structure that uses a steel frame as the main element to support the load and provide stability. This steel frame is made up of elements such as columns, beams, and bracing that are assembled to form a strong frame [25]. Bracing in buildings is used to improve the rigidity and stability of buildings, especially in the face of lateral forces such as wind and earthquakes. Bracing serves to distribute the load acting on the structure and prevent excessive deformation [26]. Based on SNI 1729-2002, this study found a structural material with the quality of BJ-37 steel, which has a tensile stress (fy) value of 240 MPa and ultimate stress (fu) of 370 MPa.

2.3. Building Structure Modeling

The steel frame building analyzed in this study is designed using specific material requirements with the following dimensions. The building spans 40 meters in length and 25 meters in width, with a total height of 32 meters, consisting of eight floors, each with a floor height of 4 meters. The structural system utilizes IWF steel profiles, where the columns (K) are constructed with IWF 500. 450.25.25 mm, the main beams (B1) use IWF 400.250. 19.12 mm, the secondary beams (B2) use IWF 300.200. 15.11 mm, and the bracing components (BC) use IWF 175.175.11.11 mm. The floor system incorporates a plate structure with a thickness of 15 mm for the roof floor section (P1) and 20 mm for the standard floor sections (P2). The steel material used is BJ-37, characterized by a yield strength (f_y) of 240 MPa and an ultimate strength (f_u) of 370 MPa, ensuring adequate strength and durability for the structure.

The geometric configuration of the building design is illustrated in Figure 1, Figure 2, and Figure 3, providing a comprehensive visual representation of the structure's layout, dimensions, and overall design concept.

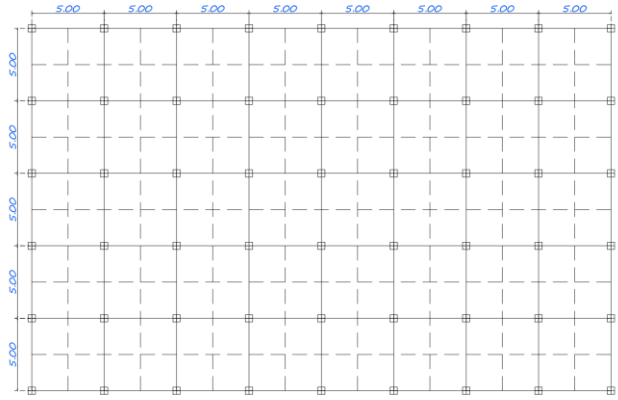

Figure 1. Building plan design.

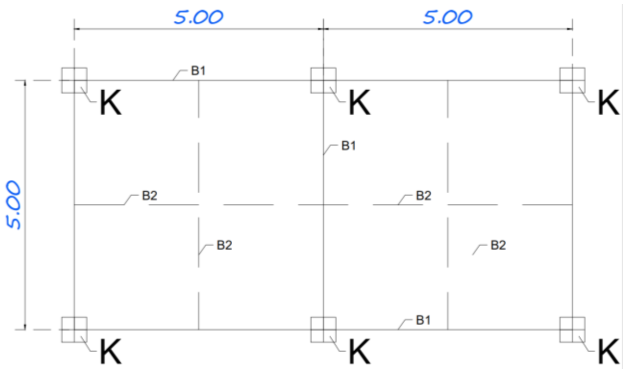

Figure 2. Column and beam section.

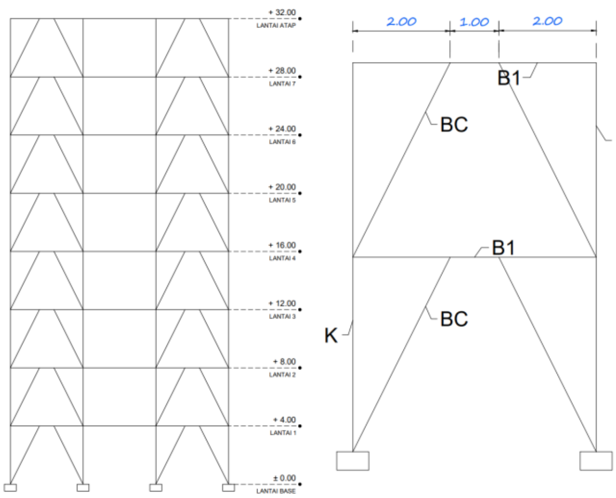

Figure 3. Side view and bracing sections.

2.4. Methodology

The design concept of this building incorporates a structural system utilizing a braced frame configuration with IWF steel profiles. The inclusion of bracing elements plays a crucial role in enhancing the building's ability to resist lateral forces, such as those induced by earthquakes. Consequently, the strategic placement and optimization of bracing locations are essential to maximize structural stability and performance under dynamic loading conditions.

This research was carried out by varying the position of the bracing placement when receiving dynamic loads. There are three variations of hangers, namely the central model with bracing in the middle of the building, the even model with bracing in the middle and corner positions, and the edge model with bracing in the corner position of the building. Each variation is then modeled using a SAP2000 soft lift with the functional conditions of the building based on SNI 1727-2020, namely live load (L), dead load (D), and earthquake load (Q), which is then calculated using a combination of forces acting on the building under normal conditions, namely 1L + 1.36 D + 1.3 Qx + 0.39 Qy.

The output of the internal forces in terms of displacement, shear force, and vibration period obtained is then analyzed to determine the performance of the structure based on the placement of the bracing. There are 3 objectives in this study, namely to find out the displacement values that occur from 3 model variations, to find out the shear forces that occur from 3 model variations, and to find out the natural period that occurs from 3 model variations. To achieve the previous goal, a research flow chart is planned as shown in Figure 4.

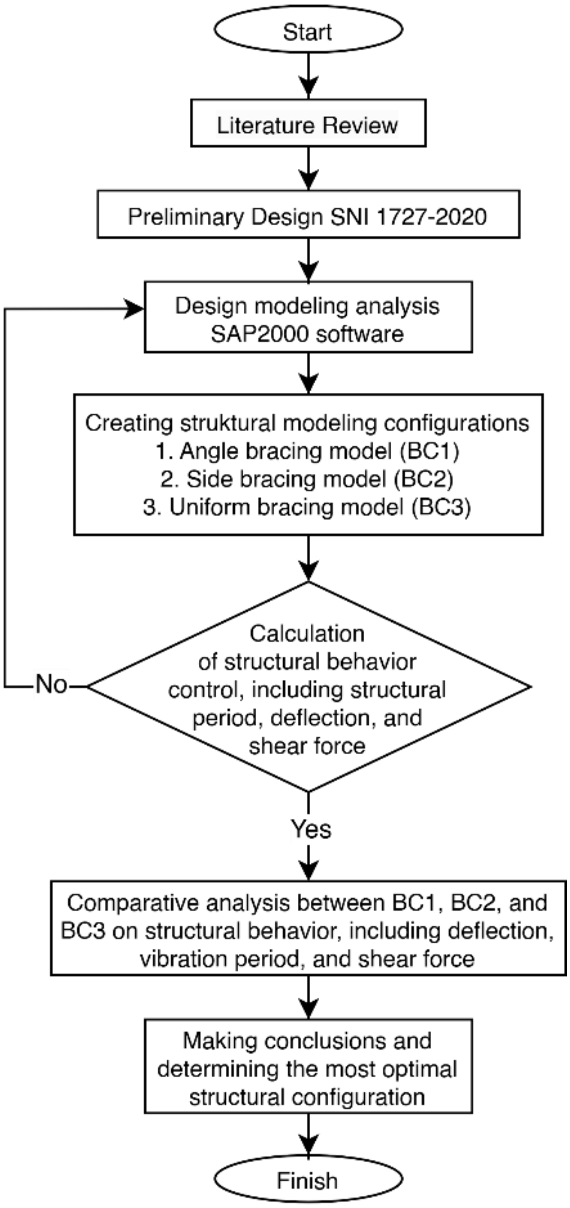

Figure 4. Flowchart of the research.

2.5. Load Building

The design of the steel frame building was a function of an office building with a location in Malang City. Designing loading regarding SNI 1727-2020 with live load, dead load, and earthquake load. Living loads include office space (240 kg/m^2), corridors (383 kg/m^2), corridors for the 1st floor (479 kg/m^2), and roofs (96 kg/m^2). Dead loads include roofs (50 kg/m^2) and typical floors (150 kg/m^2). Earthquake load with data on the function of office buildings, the location of Malang City, the SE site class, and KDS category D.

The distribution of live load areas for the 2nd to 7th floors is detailed in Figure 5, providing a clear depiction of how the loads are allocated across each floor to ensure accurate structural analysis and design. The total accumulated load, encompassing all applied loads on the structure, is comprehensively presented in Table 1, offering a detailed summary for reference in the structural analysis process.

2.1. Research Configuration

In this study, the variables were categorized into independent and dependent variables, aligned with the research objectives. The independent variable in this analysis is the placement configuration of the bracing, while the dependent variables include the displacement values, shear forces, and vibration periods, which reflect the internal performance of the structure To explore the influence of bracing placement, the structural models were divided into three distinct variations based on the configuration of the bracing placement: (1) the central placement model BC1, where bracings are concentrated at the core of the structure, (2) the edge placement model BC2, where bracings are positioned along the periphery, and (3) the evenly distributed placement model BC3, where bracings are uniformly distributed throughout the structure.

The middle placement model (BC1) features bracings arranged symmetrically at the center of the building, equidistant from each side. This configuration, as illustrated in Figure 6, concentrates the structural reinforcement within the building's core, potentially enhancing central stiffness and stability while maintaining a balanced load distribution.

Table 1. Building loading.

Story	Height (m)	Life Load (kg/m^2)	Dead Load (kg/m^2)
8	32	96.0	50
7	28	297.2	150
6	24	297.2	150
5	20	297.2	150
4	16	297.2	150
3	12	297.2	150
2	8	297.2	150
1	4	479.0	150
Total		2,358.2	1,100

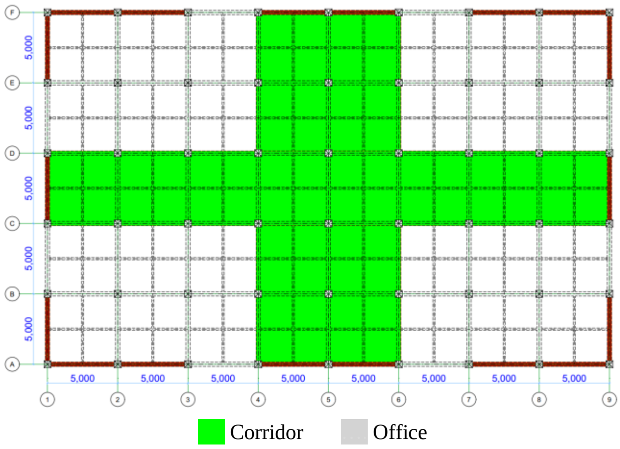

Figure 5. Area load sharing 2nd to 7th floors.

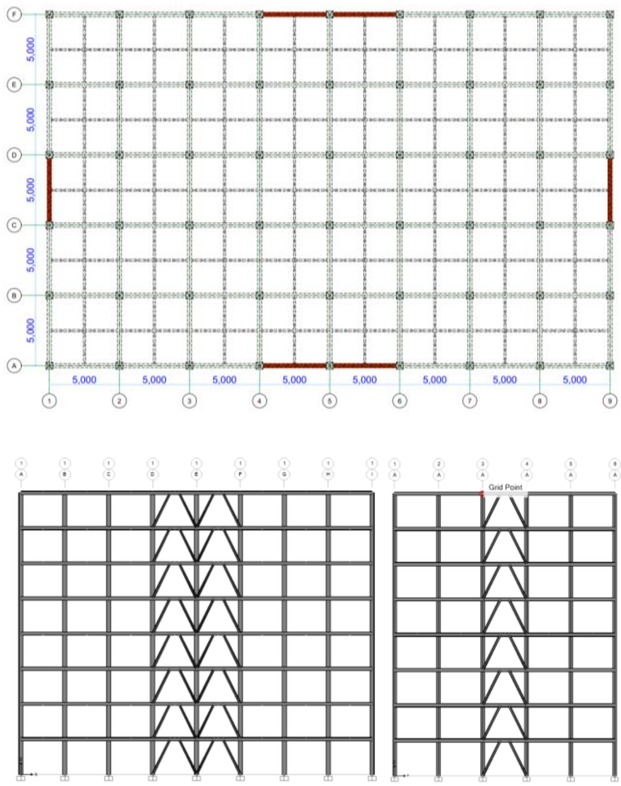

Figure 6. Placement of middle model bracing (BC1).

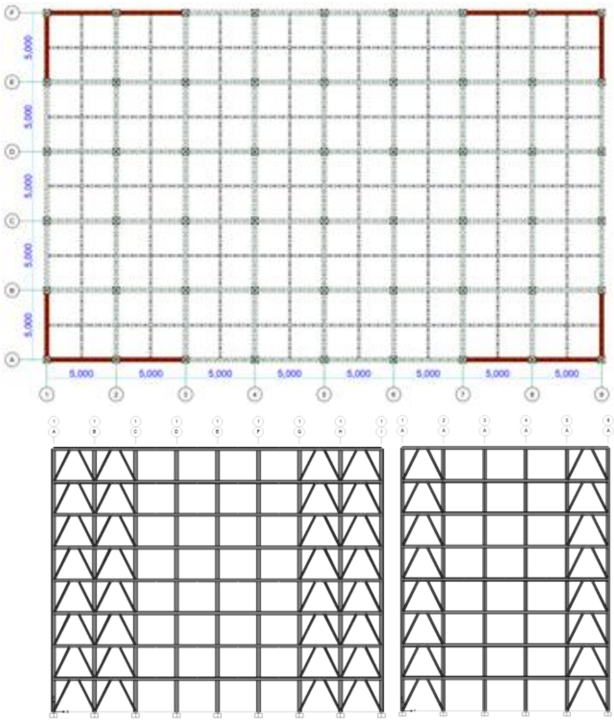

Figure 7. Placement of angle model bracing (BC2).

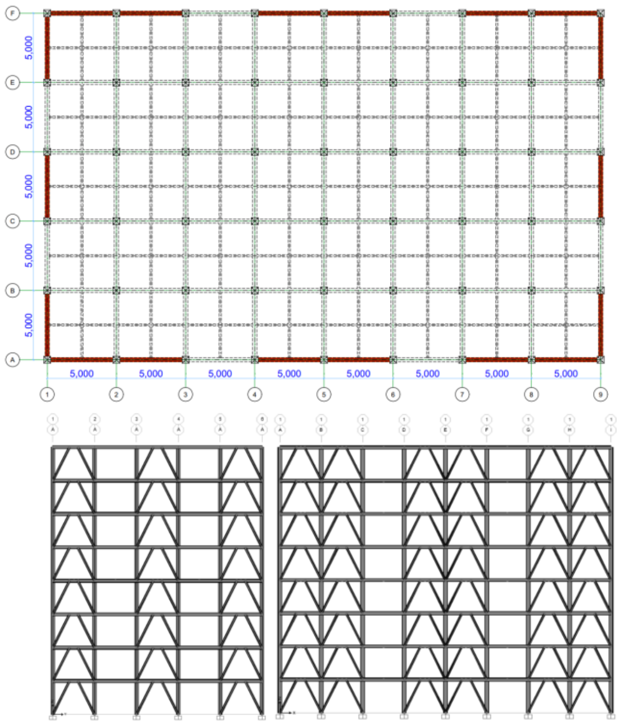

Figure 8. Placement of uniform model bracing (BC3).

The angle placement model (BC2) involves positioning the bracings at each corner of the building, as depicted in Figure 7. The uniform model (BC3) is the placement of bracing with a symmetrical position in the center and at each corner of the building, as seen in Figure 8.

2.2. Analysis Method of Steel Frame Buildings

In this study, the steel frame structure of the building will be analyzed using SAP2000 software, which is based on the concept of numerical analysis. This study will evaluate steel frames with various variations in support placement to determine several key parameters, including the displacement ratio, base shear force, and natural vibration period of each structure. This analysis will be used to evaluate the efficiency of each design, thus allowing the identification of the most optimal design to achieve the best structural stability and performance.

3. Result and Discussion

Each building model will undergo a comprehensive analysis to evaluate its structural performance, with particular emphasis on key parameters such as displacement, shear force, and vibration period. These parameters are critical in understanding how the structure behaves under various loads, particularly seismic forces. The analysis results will be compiled and scrutinized to explore the effect of different support placements on the stability and strength of the steel frame structure. By examining these results, the study aims to identify specific trends and patterns that demonstrate how variations in the support placement influence the overall performance, resilience, and load-bearing capacity of the building. This research is intended to provide valuable insights for optimizing structural design and improving the efficiency and safety of steel frame buildings in seismic and dynamic loading conditions.

3.1. Displacement

Displacement control in structural modeling is carried out so that the magnitude of displacement of the building does not exceed the allowable displacement limit. The Hotel building is included in other structural categories with the building risk category being II. The structure included in KDS = D. The displacement control calculation refers to the SNI 1726:2019 regulation. Based on article 7.12.1.1 the displacement between levels (Δ) must not exceed (Δa/ρ), where the value (ρ) is 1.3. The Equation 1 is the detailed calculation of the permit displacement limit.

$$\Delta i \leq \Delta a$$
$$\Delta a = 0{,}02h$$
$$\Delta max = \frac{0{,}02 \; x \; 4000}{1{,}3} = 61{,}54 \; mm \quad (1)$$

Structures that do not use Split K-Braced EBF have a displacement value between floors that does not exceed the permit displacement limit that has been set. Based on the output of SAP200, it is known that the displacement between floors is below 61.54 mm.

Based on the analysis conducted using the SAP2000 program for each building model, the maximum displacement values for the respective models have been calculated and are presented in Table 2, Table 3, and Table 4. These tables provide a detailed overview of the peak lateral displacements observed, serving as a key indicator of the structural performance and stability of each model under the applied load conditions.

The comparative diagrams illustrating the displacement values in both the X and Y directions for the three structural models are presented in Figure 9 and Figure 10.

3.2. Natural Vibration Period

Due to its critical role in evaluating seismic forces, the fundamental period of vibration (T) is regarded as one of the most essential variables in seismic design. This parameter directly influences the calculation of dynamic responses, including the magnitude of seismic forces acting on a structure. Accurate determination of the fundamental period is vital to ensure the safety and performance of new structures under earthquake loading conditions, as it serves as a key factor in both structural analysis and code-based design requirements [27][28].

Controlling the vibration period is essential to prevent the structure from becoming too flexible. Each structure has a specific period of vibration during which it tends to vibrate when exposed to lateral loads such as wind or earthquakes. By regulating the vibration period, it can be ensured that the structure has sufficient rigidity and can withstand lateral loads well [29].

Table 2. Displacement analysis results model BC1.

Story	Height (mm)	Δx (mm)	Δy (mm)	Drift Limit (mm)
8	4000	7.15	2.53	61.54
7	4000	11.83	4.57	61.54
6	4000	16.56	6.27	61.54
5	4000	20.68	7.81	61.54
4	4000	23.93	9.02	61.54
3	4000	25.91	9.90	61.54
2	4000	25.36	10.23	61.54
1	4000	15.51	7.54	61.54

Table 3. Displacement analysis results model BC2.

Story	Height (mm)	Δx (mm)	Δy (mm)	Drift Limit (mm)
8	4000	7.76	3.14	61.54
7	4000	12.27	5.01	61.54
6	4000	16.67	6.71	61.54
5	4000	20.41	8.03	61.54
4	4000	23.21	9.08	61.54
3	4000	25.03	9.79	61.54
2	4000	24.75	9.96	61.54
1	4000	15.73	7.48	61.54

Table 4. Displacement analysis results model BC3.

Story	Height (mm)	Δx (mm)	Δy (mm)	Drift Limit (mm)
8	4000	6.16	2.58	61.54
7	4000	9.85	4.18	61.54
6	4000	13.37	5.55	61.54
5	4000	16.39	6.66	61.54
4	4000	18.65	7.48	61.54
3	4000	20.13	7.98	61.54
2	4000	20.02	8.14	61.54
1	4000	13.26	6.16	61.54

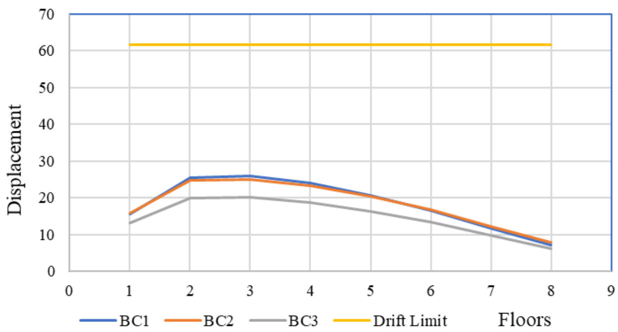

Figure 9. Ratio of displacement floors in X direction.

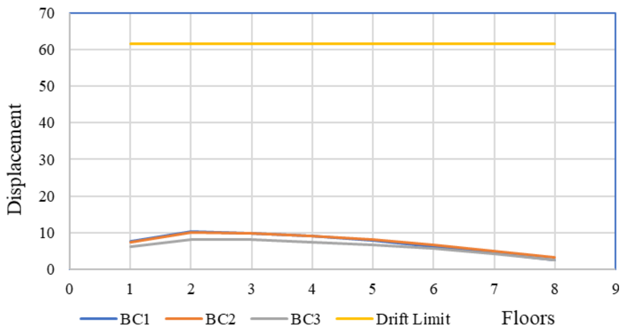

Figure 10. Ratio of displacement floors in Y direction.

Table 5. Structural vibration time in X direction.

Model	T_a (second)	T_{max} (second)	T_c (second)	Sig. (%)
BC0	1.1584	1.6217	1.225	-
BC1	0.9835	1.3769	0.973	-20.548
BC2	0.9835	1.3769	0.864	-29.449
BC3	0.9835	1.3769	0.779	-36.425

Table 6. Structural vibration time in Y direction.

Model	T_a (second)	T_{max} (second)	T_c (second)	Sig. (%)
BC0	1.1584	1.6217	1.157	-
BC1	0.9835	1.3769	0.908	-21.559
BC2	0.9835	1.3769	0.753	-34.949
BC3	0.9835	1.3769	0.657	-43.225

Table 7. Base shear forces of static analysis.

Base Shear Force	BC0	BC1	BC2	BC3
X (kN)	2,620.22	3,128.07	3,535.55	3,937.75
Y (kN)	2,056.92	2,370.70	2,613.66	2,879.58

Table 8. Base shear force dynamics analysis.

Base Shear Force	BC0	BC1	BC2	BC3
X (kN)	3209.77	3831.89	4331.05	4823.74
Y (kN)	2519.72	2904.11	3201.73	3527.49

Table 9. Base shear force dynamics analysis.

Model	Arah X (kN) Sig. (%)	Arah Y (kN) Sig. (%)
BC0	3209.77 -	2519.72 -
BC1	3831.89 (+19.38)	2904.11 (+15.25)
BC2	4331.05 (+34.93)	3201.73 (+27.06)
BC3	4823.74 (+50.28)	3527.49 (+39.99)

Based on the results of the SAP2000 analysis, the structural vibration period values of the three models are presented in detail in Table 5, and Table 6.

The results of the analysis show that the natural vibration time (T_c) in buildings equipped with bracing is smaller compared to buildings without bracing. This indicates that the addition of bracing significantly increases the rigidity of the structure. Based on the data presented in Table 5, and Table 6, the BC3 model has the smallest natural vibration period value compared to other models, so it can be concluded that the structure of the BC3 model is the most rigid and stable in responding to dynamic loads.

3.1. Base Shear Force

SNI 1726-2019 article 7.9.4.1 stipulates that the basic shear force obtained from a dynamic analysis must have a minimum value equivalent to 100% of the basic shear force of an equivalent static analysis. The fulfillment of this requirement is carried out through the comparative control of the basic shear forces resulting from the two types of analysis. The control results are presented in detail in Table 7, and Table 8, which show the conformity between the results of static and dynamic analysis in meeting the applicable standards.

Table 7, and Table 8 illustrate that the base shear forces derived from the dynamic analysis of all structural model types have surpassed the specified limit conditions, indicating the robustness of the structural responses under seismic loads. Furthermore, Table 9 provides a comprehensive summary of the base shear force values for each structural model type and includes a comparative analysis relative to the reference model BC0.

The base shear forces of all buildings equipped with bracing show a significant increase compared to the unbraced structure. This increase is attributed to the enhanced stiffness provided by the bracing system, which leads to an increase in the angular frequency and a corresponding decrease in the vibration period. As a result, the structural response to seismic loads intensifies, leading to higher shear forces being developed within the system. This behavior underscores the role of bracing in improving structural rigidity and altering dynamic characteristics under seismic excitation.

4. Conclusion

Based on the analysis that has been carried out through modeling the structure of steel frame buildings with the addition of supports in certain configurations, the results are obtained that the BC3 building model shows the most optimal structural performance. This is shown by the fulfillment of all structural performance requirements in accordance with the earthquake-resistant structure standards listed in SNI 1726-2019. The addition of the support provides an even distribution of the load, resulting in the largest displacement on the 3rd floor in the X direction with the smallest value compared to other models, which is 20.13 mm. In addition, the results of the analysis show that the uniform model has the smallest natural vibration period of 0.779 seconds in the X direction and produces the largest dynamic shear force in the X direction, which is 4,823.74 kN. This analysis emphasizes that the applied support configuration has a significant effect on the efficiency of the building's structural performance. Therefore, it can be concluded that the placement of supports on multi-storey buildings with steel frames has a significant influence on the structural capabilities of the building. The placement of supports evenly, such as in the BC3 model, has been proven to provide the most optimal structural performance compared to other building models. This shows that a properly designed buffer configuration not only improves the stability and efficiency of the structure, but also results in a more reliable building design that complies with the required performance standards.

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