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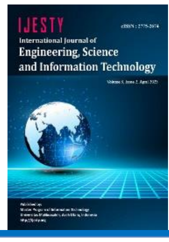

Comparative Study of Strengthened Steel Structure Behavior Using Bracing and Shearwall

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Abstract

Multi-story structures are susceptible to lateral forces, necessitating lateral stiffeners to enhance rigidity. Incorporating stiffener systems into the building's structure, particularly in steel buildings, improves rigidity by constraining structural movement. This study evaluates and compares various stiffener systems based on fundamental period (T), base shear force (V), and inter-story drift (Δx). A ten-story steel office building model underwent analysis with five variations: one without stiffeners and four with stiffeners. Two configurations were considered for the stiffened models: mid-point and edge placement. Results highlight improved structural rigidity with stiffener systems. The shearwall stiffener at the midpoint proved most effective, exhibiting 17.67% and 18.32% better fundamental period values in the X and Y directions compared to other models. Base shear forces in the X and Y directions decreased by 0.95% relative to alternative models. Notably, inter-story drift values in the X and Y directions saw enhancements of 9.67% and 34.17% over other models. Conversely, the less efficient edge-positioned bracing stiffener model yielded only an 8.96% and 9.32% improvement in fundamental period values in the X and Y directions, respectively, compared to other models. Base shear forces in the X and Y directions were 18.02% higher than alternatives. Inter-story drift values in the X and Y directions exhibited a 1.69% and 13.15% discrepancy, indicating inferior performance. In conclusion, this study underscores the superior efficacy of a mid-point stiffener system over an edge-based configuration. This positioning yields superior results, enhancing overall structural behavior and building resilience.

Keywords: *Steel Structure, Bracing, Shearwall, Fundamental Period, Base Shear.*

1. Introduction

Indonesia is an archipelagic country located in the area of the Pacific and Asian earthquake lines from low to high intensity. So that the potential for damage and collapse of multi-story buildings cannot be ignored, because multi-story buildings are structures that are very vulnerable to resisting lateral loads, especially earthquake loads. To minimize the collapse of buildings, it can be planned by considering the strength, stiffness, and stability of the building structure with structural behavior that can withstand lateral loads [1]. Steel structure is one of the structural systems that can withstand lateral loads with very good performance, because steel material has unique characteristics compared to other structural materials, relying on its high ductility and strength properties, steel structure is very suitable for areas with high levels of seismicity [2].

Based on the previous study that have been carried out, three commonly used earthquake-resistant steel structure stiffener systems are: (1) Moment resisting frame (MRF), (2) Concentrically braced frame (CBF), and (3) Eccentrically Braced Frame (EBF). Moment resisting steel frame (MRF) systems have sufficient energy dissipation capability to provide the required ductility (required ductility) but this structure is less rigid requiring larger cross-sectional sizes and expensive double-plate zone panels to meet drift requirements [4].

Bracing is an efficient system to increase rigidity and strength in resisting horizontal drift. because of the elements bracing which is installed diagonally can convert lateral forces into axial forces so that large dimensions are not needed, can efficiently meet the deflection limits through its skeletal action but does not provide a stable mechanism for energy dissipation [3] Recently a system has been developed which can reduce seismic forces for steel building structures, namely steel plate shear walls or Steel Plate Shear Wall (SPSW). SPSW is a lateral load-bearing system consisting of thin-walled vertical steel plates, connecting beams and columns around them and fixed in one or more plates along the full height of the structure forming a buttress wall. As determined by several experiments and analytical investigations, SPSW cyclic inelastic deformation exhibits high initial stiffness, is highly ductile and can absorb large amounts of energy [20] as well as thinner, lighter and more ductile steel material than most other systems. They present suitable hysterical characteristics in the plastic zone and good energy absorption capacity [4].

According to [5] in his research, the location of SPSW placement also greatly influences the behavior of high-rise buildings in responding to earthquake loads. When the SPSW is placed at the right location it can be used economically to provide the required horizontal load resistance, therefore it is very important to determine the location of the SPSW that is effective, efficient and ideal. According to [6] in his research said that the placement of a symmetrical shear wall position shows a safe value by producing internal forces, vibration time and moment force values that are smaller than the asymmetrical shear wall positions.

In Indonesia, in general, they still use the frame system bracing as a stiffener in steel portal structures, in contrast to some high-rise buildings abroad that have used SPSW. Therefore, it is necessary to carry out a comparative study regarding the behavior of the two reinforced steel frame structures bracing and SPSW with variations in the location of the placement of stiffeners located on the edge of the building structure and in the middle of the building structure. For the purpose of knowing the choice of a more effective bracing system in one of the high earthquake prone areas in Indonesia.

2. Methods

In conducting this research analysis, first collect data in the form of planning data, structural geometric data and structural element data with the assumption that analysis for steel structures is based on SNI 1729-2020 concerning Specifications for structural steel buildings and SNI 7860-2020 concerning Seismic Provisions for structural steel buildings. Loading data based on SNI 1727-2020 concerning Minimum design loads and related criteria for buildings and other structures. Furthermore, a spectrum response analysis was carried out based on SNI 1726-2019 concerning Procedures for planning earthquake resistance for building and non-building structures.

2.1. Structure

The building models to be analyzed are Model 1 (building structure without stiffeners), Model 2 (building structure with stiffeners bracing in the center), Model 3 (building structure with stiffener position bracing on the edge), Model 4 (building structure with SPSW stiffeners in the center) and Model 5 (building structure with SPSW stiffeners on the edges), with a 10-storey building including roof. Plan size 16 m x 16 m. The height between floors is 4 m. The distance between the columns is 4 m. The function of the building is used as offices. Which is located in the city of Padang, namely the location is one of the areas that has a high intensity of seismic forces. The plans and modeling of the five models are shown in Figure 1 to Figure 5 below.

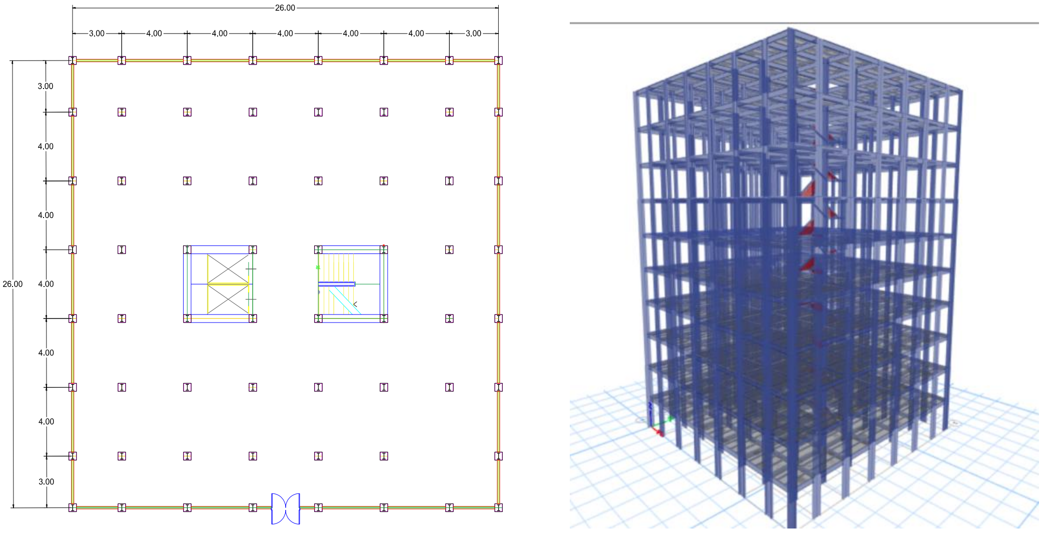

Fig 1. Plan and 3D view of model 1

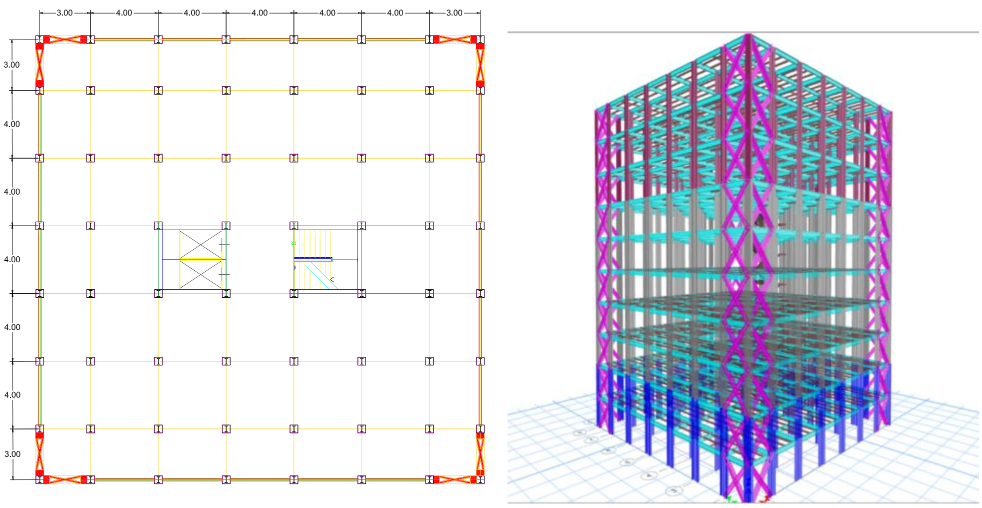

Fig 2. Plan and 3D view of model 2

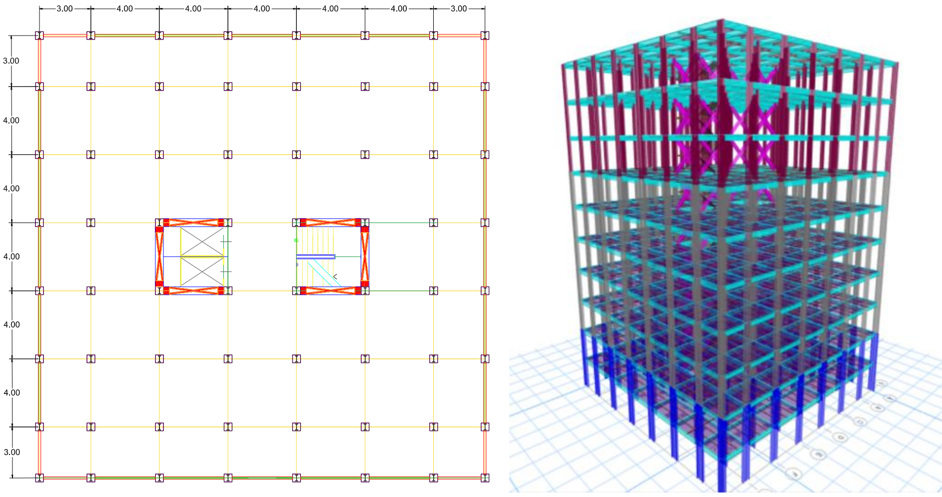

Fig 3. Plan and 3D view of model 3

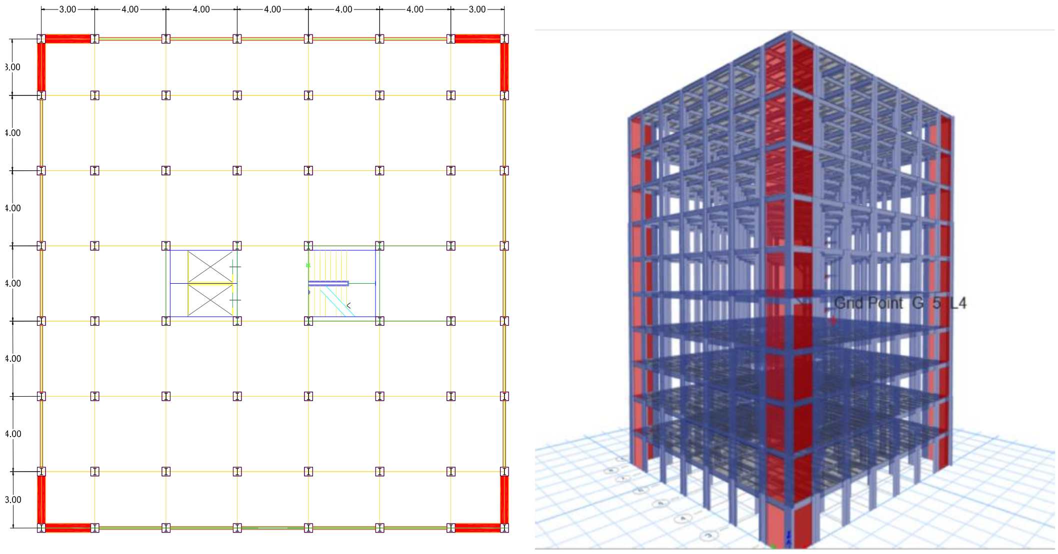

Fig 4. Plan and 3D view of model 4

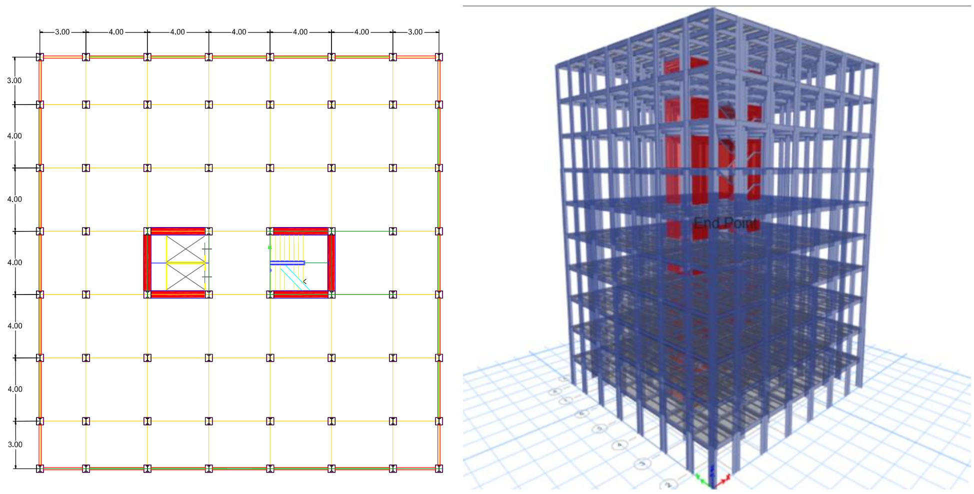

Fig 5. Plan and 3D view of model 5

2.2. Structural Materials

The steel material used is type BJ 37 based on a literature with specifications as following:

Types of steel profiles	: Profile IMF
Steel grade	: ASTM A913/A913M grade 65
Yield stress(fy)	: 410 MPa
Ultimate Strength (fu)	: 550 MPa
Density of steel	: 7850 kg/m³

2.3. Structural Element Dimensions

Sectional steel profile data for columns, beams and elements bracing used in this study are shown in Table 1. The thickness of the plate on the cross-sectional area of each frame per floor can be calculated using equation (1).

$$t = \frac{2A.\sin\theta.\sin2\theta}{L.\sin^2 2\theta} \quad (1)$$

Where:

A = Cross-sectional area in each frame per floor (m^2)
L = Span (m)
θ = Angle between the vertical bar and the diagonal plane

Table 1. Dimensions of Building Structural Element Profiles

Floor	Column	Beam	Bracing
L10	IWF 600 x 200 x 11 x 17	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L9	IWF 600 x 200 x 11 x 17	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L8	IWF 600 x 200 x 11 x 17	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L7	IWF 700 x 300 x 13 x 24	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L6	IWF 700 x 300 x 13 x 24	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L5	IWF 700 x 300 x 13 x 24	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L4	IWF 700 x 300 x 13 x 24	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L3	IWF 700 x 300 x 13 x 24	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L2	IWF 800 x 300 x 14 x 26	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19
L1	IWF 800 x 300 x 14 x 26	IWF 450 x 200 x 9 x 14	H 350 x 350 x 12 x 19

2.4. Structure Loading

The structural loading that is calculated for the design of the structure includes vertical loads (gravity) and earthquake loads (Earthquake Load). Loads that work on vertical loads (gravity), which consist of dead loads and live loads which refer to SNI Minimum Loads for the Design of Buildings and Other Structures SNI 1727-2020 [11]. The loads acting on earthquake loads use 2 methods, namely the equivalent static analysis method and the dynamic response spectrum which refers to SNI for Planning Procedures for Earthquake Resistance for Building and Non-Building Structures SNI 1726-2019.

2.5. Structural Analysis Method

The earthquake analysis method used to calculate the behavior value of the building structure is the spectrum response analysis method using numerical analysis software. Structural behavior is the property of a building against earthquake loads. In planning a structure, it must meet the structural behavior control according to the requirements of SNI 1726-2019.

2.5.1. Fundamental Period

Based on SNI 1726-2019, the fundamental structure period (T) may not exceed the multiplication result of the coefficient for the upper limit in the calculated period (C_{in}) and the approximation fundamental period (T_a). The approximation fundamental period is determined from the following equation:

$$T_a = C_t h_n^x \quad (2)$$

$$T_{max} = C_u T_a \quad (3)$$

Where:

h_n= structure height (m)
x = coefficient as in Table 2.11 SNI 1726-2019
C_{in} = coefficient as in Table 2.10 SNI 1726-2019

2.5.2. Mass Participation

Based on SNI 1726-2019, an analysis of mass participation is carried out by including a sufficient number of variants to obtain a combined variety mass participation of 100% of the mass of the structure.

2.5.3. Base Shear Force

Based on SNI 1726-2019, the base shear force is the lateral force or the total design shear that occurs at the base level. The seismic base shear force in the specified direction must correspond to the following equation:

$$V = C_s W \quad (4)$$

Where:

Cs = specified seismic response coefficient
W = effective seismic weight

2.5.3. Story Drift

Based on SNI 1726-2019, the story drift (Δ) is calculated as the difference in drift at the center of mass above and below the story. If the center of mass is not aligned in the vertical direction, it is permissible to calculate the displacement at the bottom of the story based on the vertical projection of the center of mass of the story above. The drift of the center of mass in the x-level (d_x) must be determined according to the following equation:

$$\delta_x = \frac{C_d\, \delta_{xe}}{I_e} \quad (5)$$

Where:

C_d = magnification factor for lateral drift
d_{car} = drift at the x-level which is determined elastically
$I_{It\ is}$ = earthquake priority factor

3. Results and Discussion

3.1. Fundamental Period

Based on article 7.8.6 of SNI 1726-2019, the fundamental period (Ty) used in calculating Cs is the value obtained from the numerical analysis output. The value is then compared to the minimum period value (Ta) and the maximum period value (Tmax) and may not exceed the maximum period result regulated in article 7.9.4 of SNI 1726-2019. The fundamental period of the five structural models is shown in Table 2.

Table 2. Fundamental period

Model	T_a (s)	$T_{c.x}$ (s)	$T_{c.y}$ (s)	T_{max} (s)	$T_{x\ use}$ (s)	$T_{y\ use}$ (s)
1	1,385	1,205	1,244	1,939	1,385	1,385
2	1,385	1,095	1,128	1,939	1,385	1,385
3	1,385	0,998	1,018	1,939	1,385	1,385
4	1,385	1,096	1,127	1,939	1,385	1,385
5	1,385	0,992	1,016	1,939	1,385	1,385

From Table 2, the fundamental period is compared with the fundamental period from numerical analysis result which has met $T_c < T_a$. Hence, the fundamental period used in the five models is T of 1.385 seconds in the X and Y directions. A comparison of the fundamental period of the five models is shown in Figure 6.

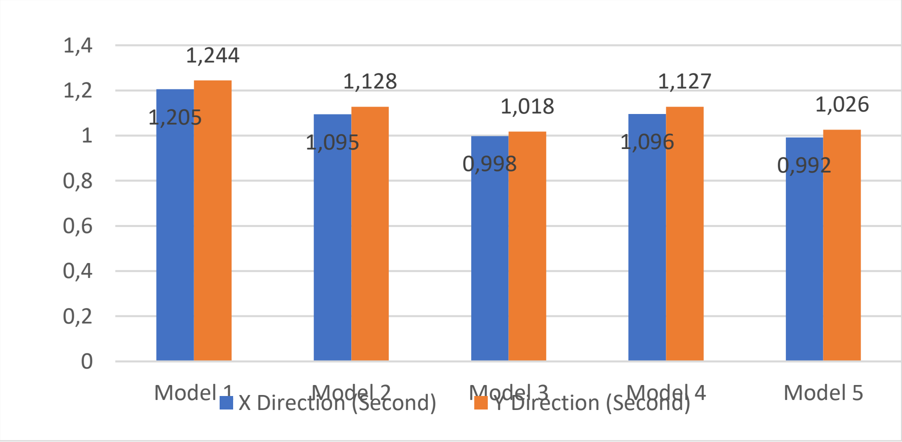

Fig 6. Fundamental period of all models

The fifth model has the smallest value compared to the other models. The second model has the greatest value among the models that are given stiffeners. The smaller the period of the structure, the greater the stiffness value of the structure. It is stated that the structure with the fifth model has greater rigidity compared to the other model structures.

3.2. Base Shear Force

The base shear force obtained from the results of dynamic analysis must not be less than or equal to 100% of the static shear force. Static and dynamic base shear forces along with the X direction scale factor are shown in Table 3.

Table 3. Base shear force in the X direction

Model	Static X (kN)	Dynamic X (kN)	Initial Scale Factor (mm/s^2)	New Scale Factor (mm/s^2)	Check 100% Static
1	2892.2785	2892.2625	1,225,831	1615.7	100%
2	3413.5248	3413.5286	1400.95	1728.680	100%
3	3398.9196	3398.9216	1400.95	1752.111	100%
4	2919.8767	2916.9798	1,225,831	1502.042	100%
5	2919.8767	2919.8878	1,225,831	1530.927	100%

The dynamic base shear force in the X direction on the five models has fulfilled 100% of the static shear force. The basic static and dynamic shear forces in the Y direction and the scale factor are shown in Table 4.

Table 4. Base shear force in the Y direction

Model	Static Y (kN)	Dynamic Y (kN)	Initial Scale Factor (mm/s^2)	New Scale Factor (mm/s^2)	Check 100% Static
1	2891.8609	2892.2474	1,225,831	1783.14	100%
2	3413.0319	3413.5286	1400.95	1821.850	100%
3	3398.4288	3398.9318	1400.95	1756.146	100%
4	2919.4551	2911.8772	1,225,831	1582.182	100%
5	2919.4551	2919.8868	1,225,831	1522.508	100%

It can be seen from Table 3 and Table 4 that the calculation of the base shear force in the five models does not fulfill the initial scale factor. Hence, the scale factor must be multiplied by the multiplier factor. The dynamic base shear force in the Y direction on the five models has fulfilled 100% of the static shear force. A comparison of static and dynamic base shear forces for the X direction and Y direction of the five structural models are shown in Figure 7 and Figure 8. It was stated that there was an increase in model 2 and model 3, in model 4 and model 5 there was a decrease in the base shear force due to the weight of the stiffening element steel plate shearwall lighter than stiffeners bracing used. It can be seen that the base shear force is influenced by the fundamental period and the weight of the structure itself.

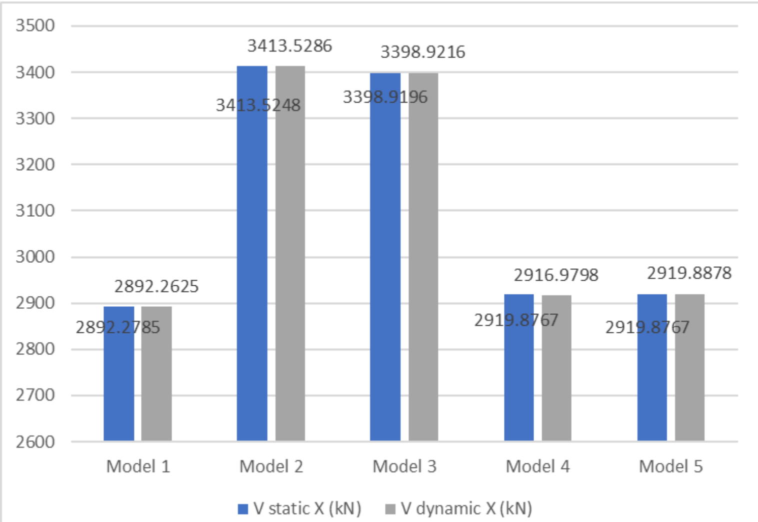

Fig 7. Base shear force in the X direction

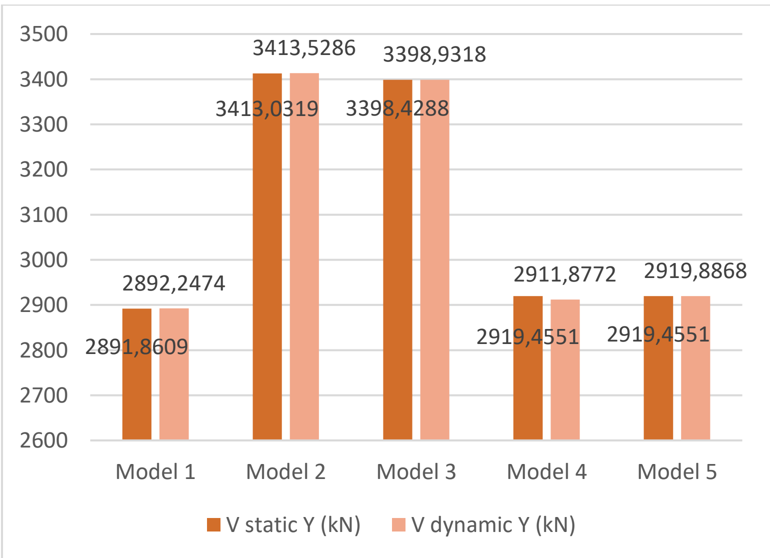

Fig 8. Base shear force in Y direction

3.3. Story Drift

The story drift must meet the requirements of SNI 1726-2019 that the deviation that occurs (Δ) must not exceed the allowable drift ($\Delta_{per\text{-}mission}$). The results of the Story drift for model 1 to model 5 are shown in Figure 9 to Figure 13, respectively. It can be seen in Figure 9 that the Story drift for model 1 in the X direction did not exceed the limit, while the Y direction was exceeding the limit. Hence, it is stated that the dimensions of the elements used have not been able to withstand the story drift due to the earthquake load that occurred. Meanwhile, for other models the story drift for both directions was still within the limit which indicated that the dimensions of the elements should be able to withstand the deviations between story due to the earthquake loads that occurred.

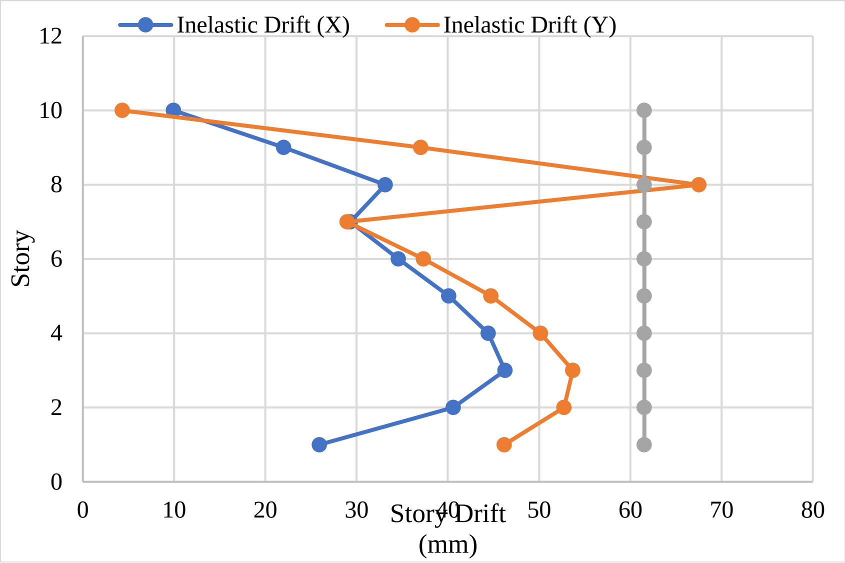

Fig 9. Graph of Story drift model 1

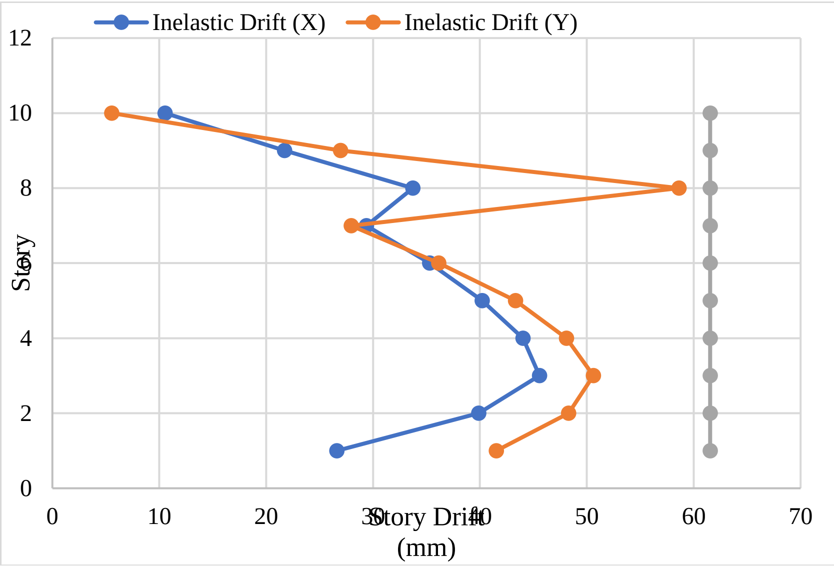

Fig 10. Graph of Story drift model 2

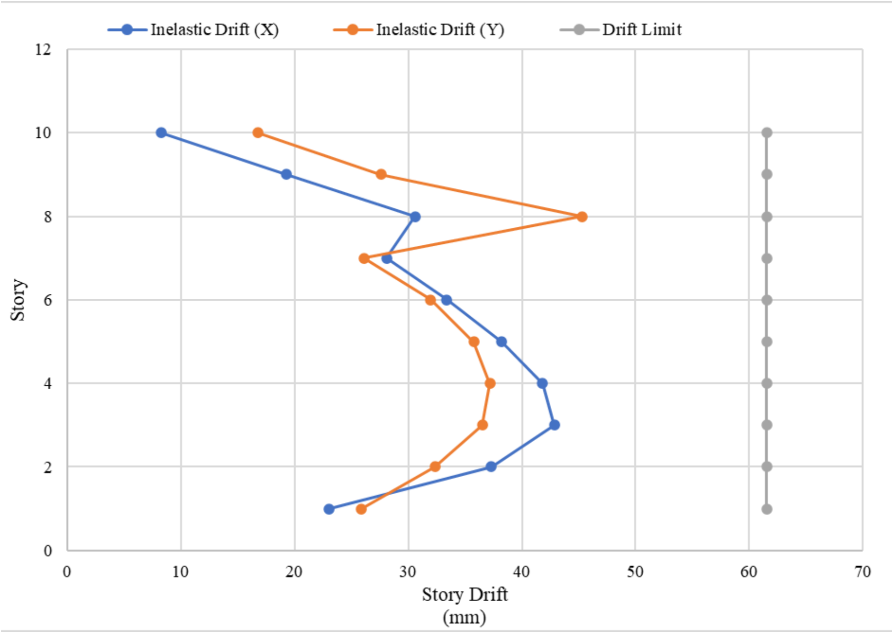

Fig 11. Graph of Story drift model 3

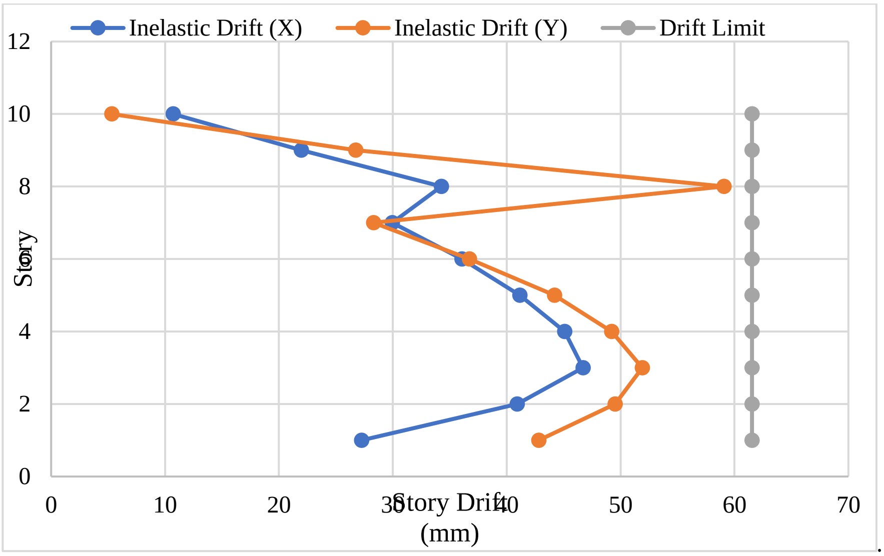

Fig 12. Graph of Story drift model levels 4

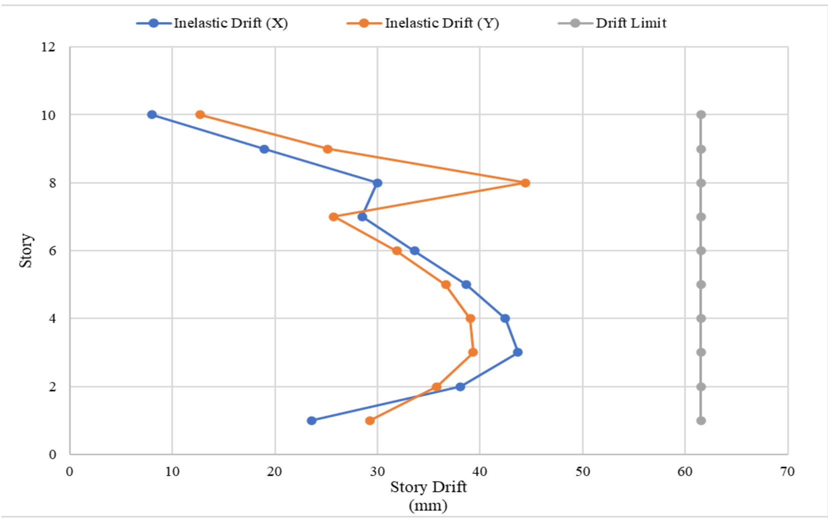

Fig 13. Graph of Story drift model 5

A comparison of the maximum story drift of the five models shown in Figure 14. The fifth model has the smallest deviation value of 44.440 mm, and the fourth model of all models that are given stiffeners has the largest drift value of 59.079 mm. The smaller the drift that occurs, the greater the stiffness value of the structure. It is stated that the structure with the fifth model has greater rigidity compared to the other model structures.

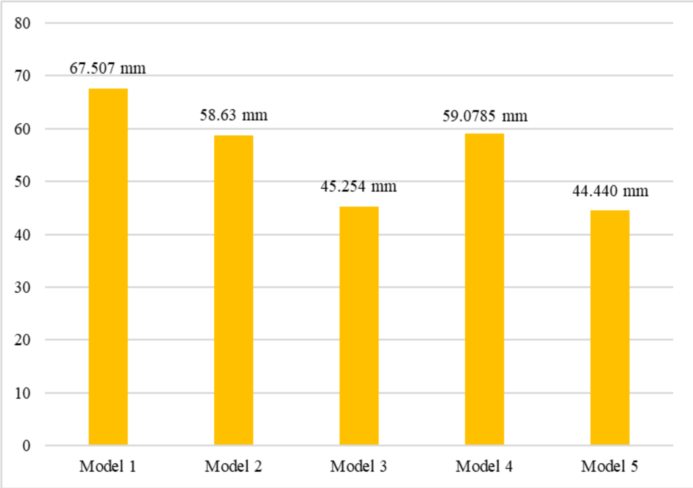

Fig 14. Comparison of maximum deviations for all models

.3.4. Dual system

The results of the comparison of the percentage of base shear between the frame system and the wall system and the bracing system are obtained from the values joint reaction. The percentage of resisting earthquake forces in the four models is shown in Table 5 below:

Table 5. Dual system controls on model 2

Sliding Style	X direction		Check	Y direction		Check
	kN	%		kN	%	
Frame ≥25%	2087.8748	61.94%	Ok	2062.0131	61.18%	Ok
Bracing ≤75%	1320.1247	39.16%	Ok	1350.9925	40.08%	Ok

It can be seen from Table 5, the calculation of the dual system control on the structure bracing (model 2) the X and Y directions have fulfilled, where the frame system is 61.94% and the bracing of 39.16%. In the Y direction it is also fulfilled, namely the frame system of 61.18% and the system bracing by 40.08%.

Table 6. Dual system controls on model 3

Sliding Style	X direction		Check	Y direction		Check
	kN	%		kN	%	
Frame ≥25%	1895.1716	56.8%	Ok	1874.5710	56.2%	Ok
Bracing ≤75%	1498.7831	44.9%	Ok	1523.8377	45.7%	Ok

It can be seen from Table 6, the calculation of the dual system control on the structure bracing (model 3) the X and Y directions have fulfilled, where the frame system is 56.8% and the system bracing of 44.9% In the Y direction it has also been fulfilled, namely the frame system of 56.2% and the system bracing by 45.7%.

Table 7. Dual system controls on model 4

Sliding Style	X direction		Check	Y direction		Check
	kN	%		kN	%	
Frame ≥25%	1911.2056	65.6%	Ok	1863.9402	64.0%	Ok
Shearwall ≤75%	1003.8323	34.4%	Ok	1055.4921	36.2%	Ok

It can be seen from Table 7, the calculation of the dual system control on the structure bracing (model 4) the X and Y directions have fulfilled, where the frame system is 65.6% and the system shearwall by 34.4%. In the Y direction it is also fulfilled, namely the frame system of 64.0% and the system shearwall by 36.2%.

Table 8. Dual system controls on model 5

Sliding Style	X direction		Check	Y direction		Check
	kN	%		kN	%	
Frame ≥25%	1673.7273	57.42%	Ok	1741.5664	59.75%	Ok
Shearwall ≤75%	1244.7667	42.71%	Ok	1177.8745	40.42%	Ok

Based on Table 8, the calculation of the dual system control on the structure bracing (model 5) the X and Y directions have fulfilled, where the frame system is 61.94% and the shearwall of 39.16%. In the Y direction it is also fulfilled, namely the frame system of 61.18% and the system shearwall by 40.08%.

It was found that the structure with model 3 and model 5 which has a stiffener position in the middle has better stiffness compared to the structure model 2 and model 4 which has a stiffener position at the edge. In line with research [8], which says that based on the results of the analysis of the structure's vibration time, the deviation value and the percentage value of each layout shearwall, shearwall layout 1 (L-shaped) and shear wall layout 2, namely shear wall layout 2 which is placed closer to the center of mass is considered to be more effective in resisting lateral loads and in line with research [14] which was carried out in his research, regarding the Dual System Control, namely based on the percentage value of lateral force absorption in the Moment Resisting Frame System, the smallest value in the X direction was 30.27% and the Y direction was 29.58% in the 5th modeling.

Meanwhile, from the results of the structural period, the smallest value was 1.34696 seconds which is located in the 5th model. The model where the shearwall is located in the middle of the structure. With a double system percentage value, the period of the structure and the small deviation between floors in resisting lateral forces, it is considered that the building structure is safer. Because the risk of damage to the building structure is considered smaller when there is shaking or movement of the building structure due to lateral loads such as earthquake loads that occurred.

The moment resisting frame system with shear walls located at the core of the building as in model 5 is considered the most effective in resisting lateral forces such as earthquake loads. As well as in research [17] which said that the braces installed on each central portal both in the longitudinal and shortening directions still showed symmetrical or stable structural behavior. The weight of the building in this study is for models that are given stiffeners shearwall experience a decrease in the weight of the building which affects the value of the base shear force on the structure. This is in line with research [16] which states that the weight of buildings using steel plate shear walls is 18% lighter than the weight of buildings using core system concrete shear walls, which results can reduce the load received by the foundation due to gravity loads and earthquake loads. And research [18] which says that with the addition of shear walls in model 1 the weight of the structure is reduced by 5.32%.

4. Conclusion

Based on the findings and discourse of this investigation, it can be deduced that the introduction of lateral bracing elements or shear walls, along with the precise placement of stiffeners, significantly influences structural rigidity. This assertion is substantiated by the scrutiny of key structural behaviour parameters, namely the fundamental period value, base shear force, and inter-story drift. Among the four models incorporating stiffeners, Model 5 exhibited superior structural behaviour in terms of fundamental period parameters, showcasing a 17.67% and 18.32% improvement in the X and Y directions, respectively, compared to Models 2, 3, and 4. Model 5 also surpassed the others in base shear forces in the X and Y directions, exhibiting a 0.95% enhancement over Models 2, 3, and 4. In terms of inter-story drift, Model 5 excelled with a 9.67% improvement in the X direction and an impressive 34.17% enhancement in the Y direction, outperforming Models 2, 3, and 4. Evidently, considering all computed indicators of structural behaviour, it becomes apparent that the structures of Models 3 and 5, featuring a central stiffener position, exhibit superior stiffness in contrast to Models 2 and 4, which have stiffeners placed at the edges. This phenomenon is attributed to the proximity of the centre of rigidity (CR) to the centre of mass (CM), resulting in enhanced structural stability. Symmetrically positioned braces or shear walls facilitate the attainment of an ideal CR position.

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