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Analysis of Effective Location of Shear Wall for High Rise Building with U – Configuration

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Abstract. Indonesia is one of the countries that is prone to earthquakes. In addition to the dead loads, superimposed dead loads, and live loads, the design of buildings in Indonesia must be concerned with earthquake loads. Installing shear walls in the building structure as the Special Moment Frame Dual System is one of a solution to withstand earthquake loads. However, the location of shear walls must be considered, especially in buildings with horizontal irregularities. This study aims to determine the optimum location of the shear walls in a 10-storey building that has U-configuration with dynamic earthquake loads. This research is a numerical simulation ran by modelling the structure with software. To know the effect of the shear wall's location on a building, several variations of the shear wall configuration with different positions have been conducted. It can be seen the lateral displacement of each floor and the shear force are the response structure to withstand the dynamic earthquake loads. Shear walls that are located close to the center of mass of the building are the optimum variation because the position of the shear wall is the closest to the core area of the building, which is the rotational axis of the building.

Keywords: high rise building, U – configuration, earthquake load, shear wall, displacement, shear force

INTRODUCTION

For areas that are prone to earthquakes, earthquake loads are the major challenge in building structure design, especially for high-rise buildings. The effect of earthquake loads is more influential in the higher building. The existence of shear walls in a building serves to reduce the lateral displacement in building and avoids the harmful effects of earthquake disasters [10]. To reduce the effect of earthquake loads, various engineering designs are carried out by combining structural systems, one of which is by applying shear walls. Shear walls are reinforced concrete slabs that are installed in a vertical position in buildings that are proportioned to resist a combination of shear, moment, and axial force [3]. Shear wall serves to increase the rigidity of the structure so that it can withstand shear forces as the building height increases. Several previous research have been carried out on shear wall structures in different variations of building plans.

There are several factors that can affect the performance of shear walls; the position of shear walls, the type of materials and the configuration [12]. Concrete material is widely used as a shear wall structural material. The stirrup distance influences the shear wall strength. In a shear wall design, it needs tighter hoop spacing for increase stiffness and ductility [13]. In the same building volume but have different positions and shapes of shear wall, it can affect the structure stiffness to resist lateral loads [9]. While the shear wall where is placed parallel to the XY axis which is close to the center of mass has the most optimum strength to resist the loads [14]. Due to variations in building plans that are not always regular, the position of the shear walls must be considered to provide effective and efficient structural strength. Therefore, to determine the best position of the shear walls in a building with an irregular horizontal configuration, U-shaped plan, the study was carried out by applying several variations of the shear walls position.

METHODOLOGY

The research was conducted by numerical modelling using ETABS program which is finite element-based computer program. The data is analyzed in 3D portal structure with 4 variations model, 1 model is without shear wall and 3 models with different shear wall locations for the X and Y directions. The modelling is purpose to analyze and compare the behavior of the structures of high-rise buildings due to both vertical loads and earthquake loads. The building in this study is an office 10 - storey building located in Jakarta. Height of each floor is 4 m. The following Figure 1 below is a typical plan for a variation model without a shear wall in the building.

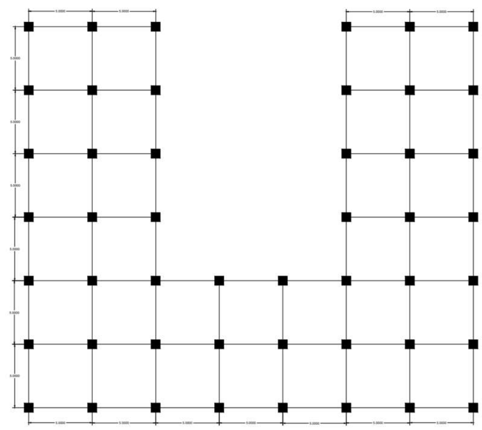
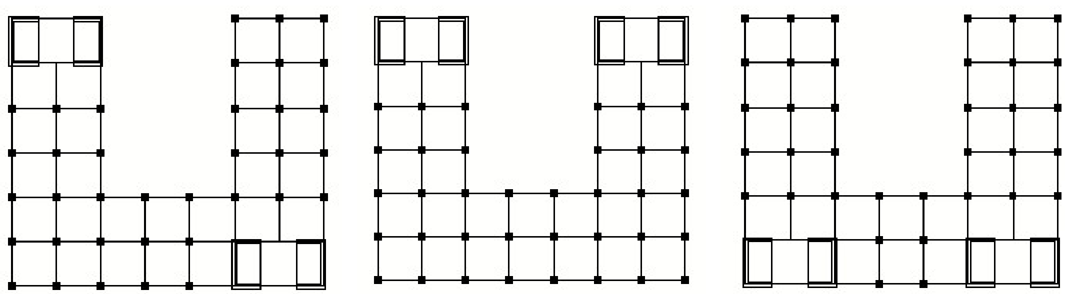


FIGURE 1. Building Plan-U Configuration without shearwall (V0)

It can be seen in Figure 1 above that the distance between columns is typical 5000 mm both the distance between the columns in the X direction and Y direction. The configuration of various shear wall locations in the building is shown in the following figure.



(a) (b) (c)

FIGURE 2. Building Plan Configuration With Shear Wall (a) V1, (b) V2, and (c) V3

Figure 2 (a) is the first variation where shear walls is located on the top left and bottom right. Meanwhile, in the second variation which can be seen in Figure 2 (b), shear wall is given at the top of the U configuration. The last variation can be seen in Figure 2 (c) where the shear wall is only placed at the bottom of the U configuration plan.

The Earthquake load which is used in the modeling is a dynamic earthquake load or response spectrum in accordance with Indonesian regulations and adapted to the location of the building. The graph of the response spectrum used in the loading in this study can be seen in Figure 3.

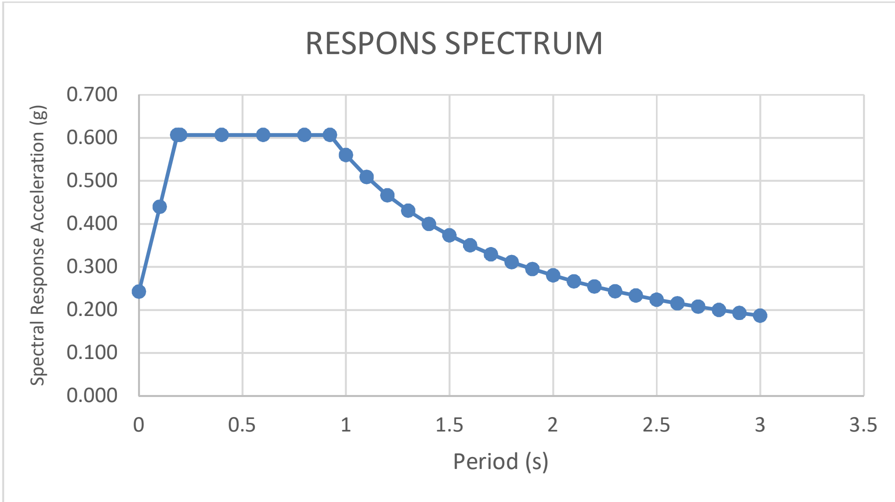


FIGURE 3. Jakarta Design Earthquake Spectrum Response

The structural data is a structural model of a combination of truss and shear walls in a 10-storey building which has irregular horizontal configuration with a function as an office. The beam and slab materials in this study used 30 MPa concrete. While the material for the columns and shear walls used 40 MPa concrete. For flexural and shear reinforcement are steel reinforcement which have yield stress 400 MPa and 240 MPa. The dimension of the structural component is obtained by preliminary calculation. The beam dimension is 200 mm x 350 mm and the largest column is 500 mm x 500 mm. The plate thickness is 120 mm and the dimension of the largest shear wall is 250 mm. For more details, the component specifications of the building can be seen in Table 1 below.

TABLE 1. Specifications for Building Elements

Story	Column (mm)	Beam (mm)	Slab (mm)	Shear Wall (mm)
1 – 4	500 x 500	200 x 350	120	250
5 – 7	400 x 400	200 x 350	120	200
8 – 10	300 x 300	200 x 350	120	150

The modeling in this study refers to several Indonesian National Standards, namely SNI 2847-2019 regarding Structural Concrete Requirements for Buildings, SNI 1727-2013 concerning Minimum Loads for Designing Buildings and Other Structures, and SNI 1726-2019 concerning Procedures for Planning Earthquake Resistance for Building and Non-Building Structures.

RESULT AND DISCUSSION

The results of the analysis that was obtained from the modelling program are the behavior of the structure in the form of the natural period and mode shape, story drift, shear story, and the stiffness of the structure. Those results are used in structural design and to draw conclusions about the response of the structure itself so the effect could be seen and the effectiveness due to the differences in shear wall thickness and the placement which has the best effect on the building structure.

Period

The period of the structure is the time required for the structure to make one full rotation in accepting the load [15]. In other words, the period of the structure is the time required for the structure to return to its original shape after receiving earthquake forces. In Table 2 below shows that the decreasing value on the structure period for each variation is quite noticeable, especially in the buildings that use shear walls as the lateral system. The V0 variation model where the building is not provided with shear walls experienced the largest period. While, the period for all variations of buildings that was given shear walls, was decreased. This shows that the availability of shear walls makes the building more rigid.

TABLE 2. Period

Variation	Period (sec)
V0	3.744
V1	2.625
V2	2.394
V3	2.325

The largest period among the three building models with shear walls is experienced by variation V1 where the location of the shear walls when viewed from the Y axis of the shear wall pair is given on the top and bottom sides of the building plan as can be seen in Figure 2. While the smallest vibration period is experienced by variations V3 where the location of the two pairs of shear walls when viewed from the Y axis is given only at the bottom of the building plan as can be seen in Figure 4. This can be caused by the differences in the placement of the shear walls. When viewed from the Y axis on the basic building plan without shear walls, the number of columns on the right and left sides are 7 columns. While on the X axis on the basic building plan without shear walls, the number of columns on the top side is 6 columns, and the number of columns on the bottom side is 8 columns. In the V3 model, both pairs of shear walls are placed in a direction that has a higher number of columns than the other two variations, causing the model to be more rigid than the other variations.

TABLE 3. Mode Shape

VARIANT	Mode Shape	UX	UY	RZ	Description
V1	1	0,639	0	0	*Translation X*
	2	0	0,624	0	*Translation Y*
	3	0	0,004	0,619	*Rotation*
V2	1	0,628	0	0,030	*Translation X*
	2	0	0,631	0	*Translation Y*
	3	0,027	0	0,597	*Rotation*
V3	1	0,633	0	0,023	*Translation X*
	2	0	0,631	0	*Translation Y*
	3	0,022	0	0,607	*Rotation*

Table 3 shows the mode shape experienced by each variation of the model. The V2 and V3 models in the first shape mode show a translation in the X direction and a slight rotation. And in the second shape mode, the V2 and V3 models show translation in the Y direction. While the V1 variation's first mode shape, the structure experiences translation in the X direction. For the second mode shape of V1 variation, the structure experiences translation in the Y direction. And the third mode shape of V1 variation, the structure rotates. This is due to the asymmetrical shape of the building configuration and the placement of shear walls on the weak and strong axes of the building. In addition, all variations of the building model with shear walls which are V1, V2, and V3 also have a smaller period compared to the V0 building model without shear walls. Therefore, it can be concluded that the structure with the type of V1 variation has more durability in torsion.

The first mode shape in variations V2 and V3 apart from translation in the X direction, it has also undergone rotation where the value is quite small. While the period experienced by variations V2 and V3 is slightly smaller than the n period in variations V1. This shows that variations V2 and V3 are slightly more rigid than variation V1 because the difference in period values is not that significant but also does not necessarily have better durability to torsion than variations V1 which are more symmetrical than the variations V2 and V3. In other words, the durability of torsion is not only seen from the period but also from the more symmetrical configuration of the shear wall placement including the X-axis and Y-axis.

Shear Storey

Based on SNI 03-1726-2019 the value of the dynamic base shear should not be less than 100% of the base shear calculated using the equivalent static analysis method. If this condition is not met, then the scale factor needs to be corrected based on the ordinate of the spectrum variance.

Table 4 shows that the dynamic base shear requirements have not met the 100% static base shear requirements both in the X direction and in the Y direction. Therefore, the scale of the spectrum response needs to be enlarged as shown in the table below. In the V0 variation model, the dynamic shear force that occurs is much smaller than the variation model with shear walls so that the magnification scale that is required is also larger than the scale factor in the V1, V2, and V3 variation models. This means that structures with shear walls are more rigid than structures without shear walls.

TABLE 4. Response Spectrum Scale Up Factor

Variant	$V_{dynamic}$ (kN)		V_{static} (kN)		X – dir	Y – dir	Scale Up X – dir	Scale Up Y – dir
	V_{base} X	V_{base} Y	V_{base} X	V_{base} Y				
V0	980,46	989,77	3344,72	3344,72	Not OK	Not OK	3,41	3,38
V1	1245,30	2020,96	3527,10	3527,10	Not OK	Not OK	2,83	1,75
V2	1259,08	2083,83	3526,66	3526,66	Not OK	Not OK	2,80	1,69
V3	1289,00	2092,00	3527,53	3527,53	Not OK	Not OK	2,74	1,69

The base shear and the story shear presented in the figures and tables below have been multiplied by the scale up factor to meet the requirements of SNI 03-1726-2019. Table 5 below is a comparison of the period of the structure with the resulting base shear of the structure. The period of the structure is also one of the factors that can affect the base shear in the building. The decrease in the period affects the magnitude of the base shear received by the building, where the increase in the base shear is proportional to the decrease in the period.

TABLE 5. Period and Base Shear of The Structure

Variation	Periode (s)	Base Shear X (kN)	Base Shear Y (kN)
V0	3.744	3344.35	3365.20
V1	2.625	3523.56	3524.79
V2	2.394	3524.32	3540.86
V3	2.325	3525.62	3554.73

The value of the base shear presented in the table above is the base shear in the first mode shape because the first mode shape is the first shape of the building after the building receives earthquake forces from the base. Taking the base shear value from mode 1 is also to avoid any form of twisting or rotation in the building contained in the following modes. From the results of this comparison, it is found that the period of the structure is inversely proportional to the base shear of the structure. Where the V3 variation which has the largest base shear on both the X-axis and Y-axis, experiences the smallest period compared to other variations. This corresponds to the fact that a small period will result in a larger base shear used in the design [4].

Figure 4 represents a graph of the shear force of each story after the scale up. The shear story does not have any significant difference for all structural models where the shear story in both the X direction and Y direction have almost overlapping graphs.

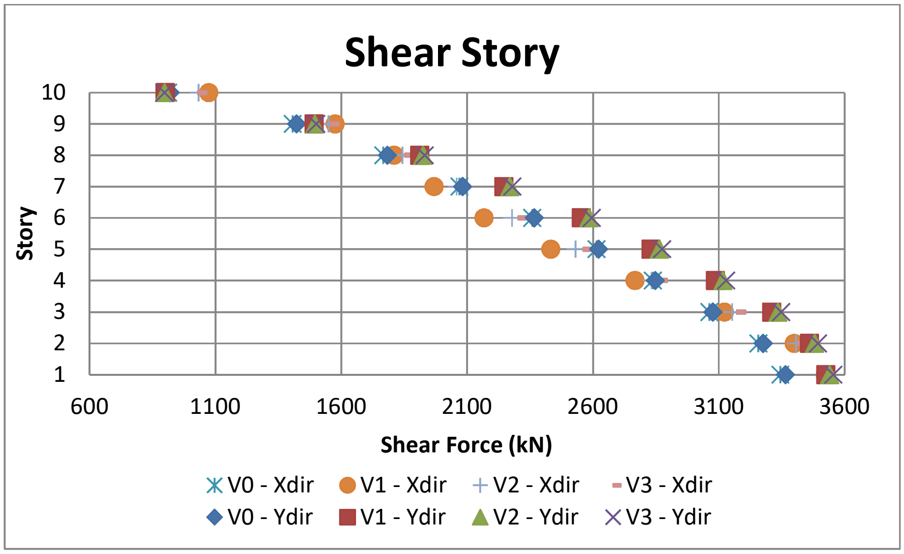


FIGURE 4. Shear Story

In detail, the comparison for the story shear for each variation on the X-axis and Y-axis experiences slight difference. In the V0 variation, the story shear experienced by each floor from the 1st floor to the 10th floor on the Y axis is greater than the story shear that occurs on the X-axis. This shows that for a building plan with a U-configuration, the shear force is greater on the Y-axis due to its asymmetrical and U-shaped configuration where 2/3 of the center is empty. Similarly, the V1, V2, and V3 variation models generally have the shear story on the Y-axis that are greater than the shear story on the X axis due to the shape of the building configuration and the placement of a longer shear wall on the Y-axis. However, on the 9th and 10th floors, in the three variations model with shear walls, the story shear in the X-axis has increased that it becomes greater than the shear story on the Y-axis because the shear wall thickness on the floor is thinner than floors 1 to 7. This means that the location and the thickness of the shear wall influence the performance and effectiveness of the shear wall in receiving shear forces [6].

Story Drift

Before analyzing the story drift, it must be ensured that the drift that occurs in each model does not exceed the allowable drift. The lateral drift between floors must always be checked to ensure the stability of the structure, to prevent damage to non-structural elements, and to ensure the comfort of building users. Based on SNI 03-1726-2019, the drift between floors of the design level should not exceed the drift between floors of the allowable level. The determination of the design level drift (δ) shall be calculated based on the difference in the deflection at the center of mass at the top and bottom stories. The center of mass deflection at level x (δ_x) is calculated by multiplying the value of Cd which is the amplification factor/magnification of the deflection of 5.5 with the value of δ_{xe} which is the deflection at the required location by elastic analysis and then divide it by the value of I_e which is the priority factor of the earthquake based on building function and risk category.

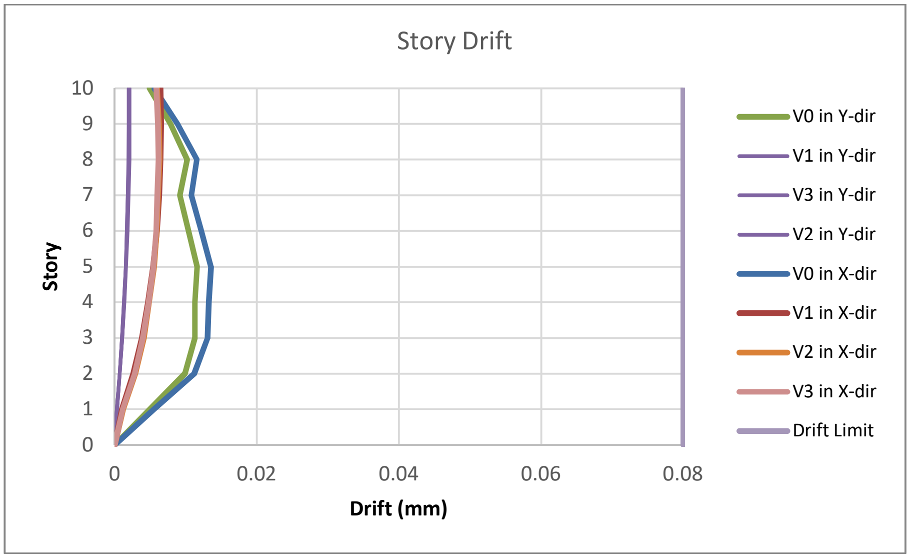


FIGURE 5. Story Drift

The Figure 5 above is a comparison graph between the story drift and the allowable drift for all variation of the structural models. In the graph above, the story drift is still below the allowable drift limit both in the X direction and in the Y direction. In addition, figure 5 also shows that the V0 variation model where the building is without shear wall experienced the most significant story drift. This indicates that the presence of shear walls in the structure can increase the stiffness of the structural system that reduce the deflection that occurs due to earthquake forces in the same direction as the placement of the shear walls. In addition, the story drift in the Y direction has a smaller value compared to the story drift in the X direction for all variation models because the shape of the building plan with the U-configuration has a strong axis in the Y direction.

Figure 6 and Figure 7 below are graphs of the comparison of the story drift between the three variations given the shear walls in this study. The value of the story drift of the building is different because it is influenced by the location and dimensions of the shear wall [5].

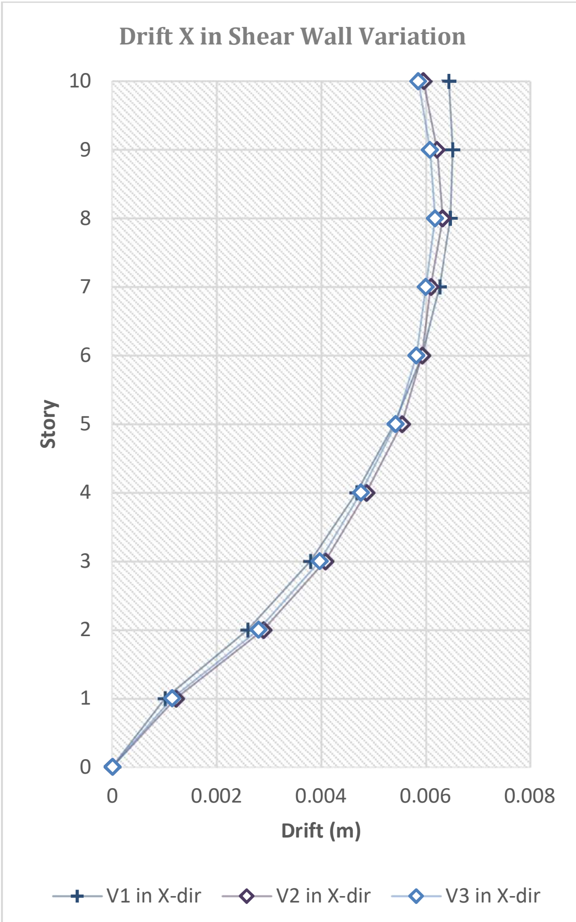


FIGURE 6. Story Drift in X direction

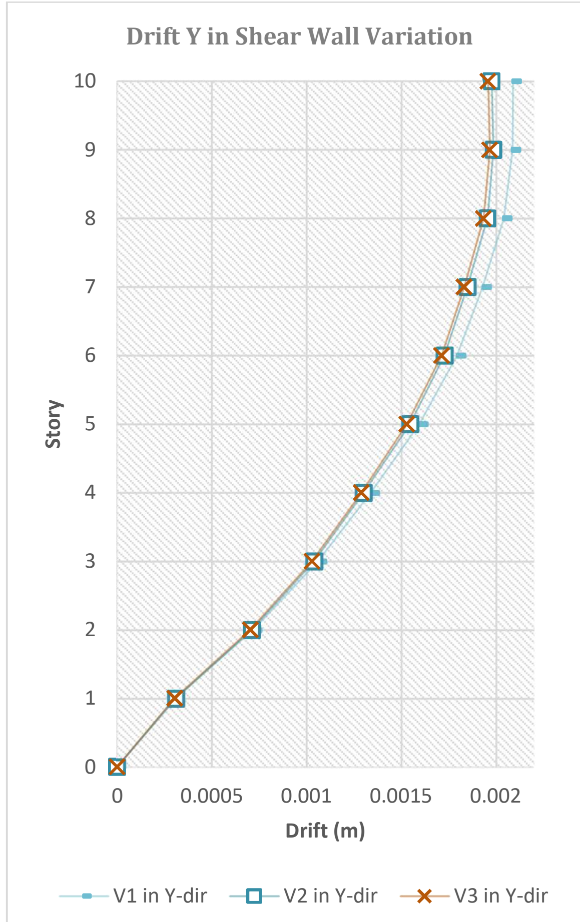


FIGURE 7. Story Drift in Y direction

In figure 6 which shows the story drift on the X axis, the V1 variation experiences the smallest drift from the 1st floor to the 4th floor. On the 5th floor to the 10th floor, the smallest drift in the X direction is experienced by the V3 variation while the V1 variation experiencing the largest drift. Likewise, in figure 7 which shows the story drift on the Y axis, the V1 variation experiences the smallest drift from the 1st floor to the 4th floor and the story drift increases from the 5th floor to the 10th floor the drift. As for the V3 variation, on the 1st floor to the 4th floor experiences a drift that was not much different but then from the 5th floor to the 10th floor the drift decreases to the smallest between the other variations.

That is because the 1st floor to the 4th floor has thicker shear wall dimensions than the 5th floor to 10th floor. The reduced thickness of the shear walls influences the performance and the effectiveness of the shear walls in receiving shear forces. It can be concluded that the structures with shear walls placed in the center of mass of the building can produce a smaller drift than the structures with shear walls placed on the outside of the structure plan.

TABLE 6. Roof Displacement

Variation	Roof Displacement X-dir (mm)	Roof Displacement Y-dir (mm)
V0	397.532	342.105
V1	193.021	59.633
V2	192.041	57.321
V3	188.370	56.788

In addition, shear walls also provide lateral stiffness to prevent the roof or floor above from swaying excessively. This is also in line with the roof displacement experienced by the structure that shown in Table 6 above. The largest roof displacement is experienced in V0 variation where the building is without shear wall. While the smallest roof displacement is experienced in V3 variation. The V3 has pairs of shear walls placed in a direction that has more columns than the other two variations. They are placed closer to the center of mass area of the structure compared to other variations. Therefore, the model becomes more rigid compared to other variations.

Story Stiffness

The story stiffness for all variation models can be seen in Figure 8 and Figure 9 below. The V0 variation which the building is without shear walls has the smallest story stiffness in the X direction and Y directions. While the buildings variations with shear walls which are V1, V2 and V3 have higher story stiffness. This proves that the shear walls increase the rigidity of the structure and the stability of the structure.

In Figures 8 and 9 below, it is generally seen that the story stiffness decreases as the number of floors increases. Because the load carried by the column on the top floor is smaller than the load carried by the column on the floor below. The largest story stiffness occurs in the Y direction due to the shape of the U-configuration building plan which has 2/3 empty parts in the center, causing the building to become more rigid in the Y direction.

Comparison of story stiffness for the buildings that has shear walls, V3 variation has the greatest story stiffness in the X direction and Y directions. Because the placement of the shear walls located at the center of mass of the building is the most effective variation because this type of shear wall is closest to the core area of the building which is the axis of rotation of the building.

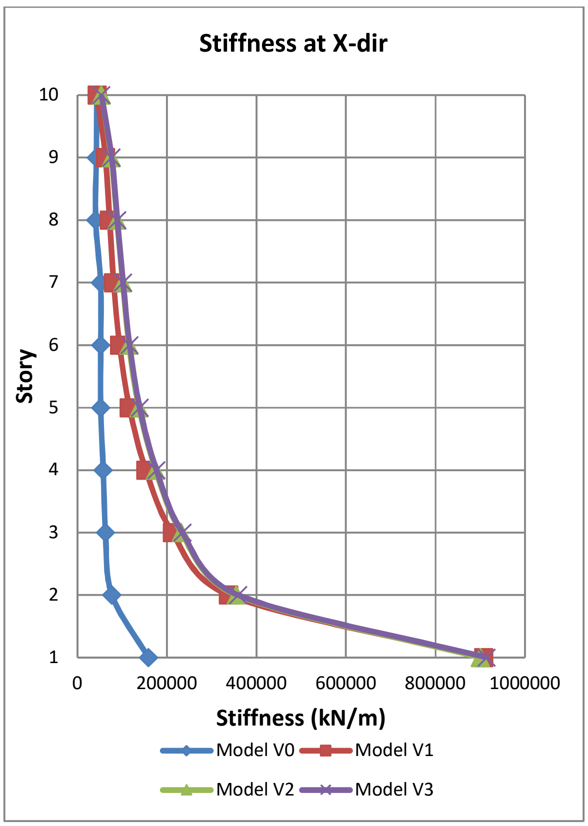


FIGURE 8. Story Stiffness in X – direction

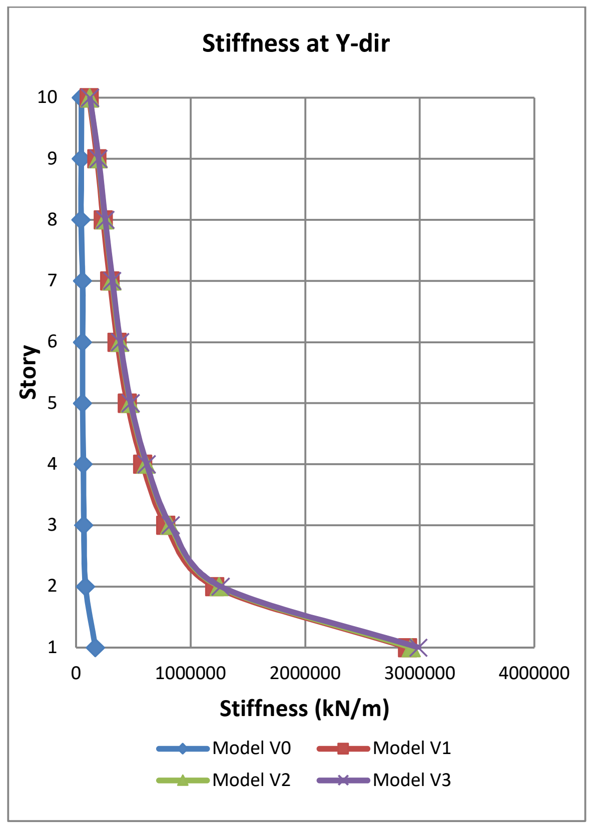


FIGURE 9. Story Stiffness in Y – direction

CONCLUSION

The period of the V0 variation where the building is without shear walls has the largest period compared to V1, V2, and V3 variation, where the building is provided with shear walls. Therefore, the smaller period experienced by the structure means more rigid structure. Among the three variations of the building that has the shear walls, the V3 model has the smallest period due to the placement of the shear wall which is closer to the center of mass of the building. However, the V1 variation has the better durability in torsion among other variations.

The result shows that the period is inversely proportional to the base shear. The increase in the base shear is proportional to the decrease in period. Where the V3 variation has the largest base shear on both the X and Y axes, it also experiences the smallest period compared to other variations.

The story drift for all variations is still below the story drift limit both in the X direction and in the Y direction. The largest story drift is experienced by the V0 variation where the building is without shear walls because the availability of shear walls in the structure can increase the stiffness of the structure, so it can reduce the deflection that occurs due to earthquake forces.

The position of the shear wall in the V3 variation has the smallest story drift and the smallest roof displacement, this is because the position of the shear wall is the position where the center of rigidity of the building is closest to the center of mass.

Building structures with shear walls have a greater structural rigidity than those without shear walls, this can be seen from the results of the structural behavior for the V0 model where the structure has the smallest story stiffness. Other than the placement of the shear walls closer to the center of mass of the building, the configuration of the placement of the shear walls must also be considered to be more symmetrical covering the X-axis and Y-axis in order to achieve the most optimal shear wall performance.

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