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Earthquake Resistant Building Structure Design Study Using Steel Plate Shear Wall System (SPSW)

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ABSTRACT

Multi-story building structures are vulnerable to lateral forces, especially due to forces caused by earthquakes. Because the higher the building, the greater the lateral deflection that occurs on the upper floors. Indonesia is one of the countries that has high earthquake intensity. One area that has high earthquake intensity is Yogyakarta. The structural building that will be reviewed and analyzed is a 10-story hotel. The development of science and technology has given rise to one solution to improve the performance of tall building structures, namely by installing steel plate shear walls. Steel plate shear walls are a lateral load-resisting system consisting of solid vertical steel plates connecting surrounding beams and columns that are installed along the height of the structure to form a supporting wall. Designing earthquake-resistant buildings with the addition of a steel plate shear wall system provides a suitable structural system to withstand lateral forces during an earthquake. The use of this system can be a recommendation, to be able to utilize steel material as a building structural material by considering the advantages of using the steel material within the limits of applicable regulations, ASCE 7-10 and AISC 341-10. In the analysis of the building structure, the influence of dynamic earthquake loads is reviewed using the SAP 2000 auxiliary program.

Keywords: *Steel plate shear wall; horizontal boundary element; vertical boundary element; deflection; lateral displacement*

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ABSTRACT

Struktur bangunan bertingkat rawan terhadap gaya lateral, terutama akibat gaya yang ditimbulkan gempa bumi. Sebab semakin tinggi bangunan, defleksi lateral yang terjadi semakin besar pada lantai atas. Indonesia merupakan salah satu negara yang memiliki intensitas gempa tinggi. Salah satu daerah yang mempunyai intensitas gempa tinggi adalah Yogyakarta. Bangunan struktur yang akan ditinjau dan dianalisis yaitu hotel 10 lantai. Perkembangan ilmu pengetahuan dan teknologi telah memunculkan salah satu solusi untuk meningkatkan kinerja struktur bangunan tinggi yaitu dengan pemasangan dinding geser pelat baja. Dinding geser pelat baja adalah sebuah sistem penahan beban lateral yang terdiri dari plat baja vertikal padat yang menghubungkan balok dan kolom di sekitarnya yang terpasang sepanjang ketinggian struktur sehingga membentuk sebuah dinding penopang. Perancangan bangunan gedung tahan gempa dengan penambahan sistem dinding geser pelat baja, menyajikan sistem struktur yang layak untuk menahan gaya lateral selama gempa bumi. Penggunaan sistem ini dapat menjadi rekomendasi, agar dapat memanfaatkan material baja sebagai material struktur gedung dengan mempertimbangkan kelebihan penggunaan material baja yang digunakan dengan batasan peraturan yang berlaku, ASCE 7-10 dan AISC 341-10. Dalam analisa struktur bangunan ditinjau pengaruh beban gempa dinamik dengan menggunakan program bantu SAP 2000.

Keywords: *Steel plate shear wall; horizontal boundary element; vertical boundary element; deflection; lateral displacement*

INTRODUCTION

The increasing population growth has increased in physical needs, including for office buildings and housing. This is especially felt in big cities. One answer to solving this is by building buildings in a vertical direction. When designing a multi-story building, it must be designed to be earthquake-resistant because the building will experience vibrations due to ground acceleration caused by earthquakes which can occur at any time.

Designing earthquake-resistant building structures is an absolute must, especially in earthquake-prone areas such as Indonesia. To be able to withstand earthquake forces, designers and structural experts design a building based on a structural system. This structural system is created based on existing regulations. To be able to withstand this load, a strong structure needs to be designed. In earthquake-resistant tall buildings, the forces that occur are quite large so it is necessary to use rigid elements that cause small deformations (deflections). Therefore, steel material is used as the main structure and a rigid structure in the form of a steel plate shear wall to withstand a combination of shear forces, moments, and axial forces that arise due to earthquake loads and wind loads[1].

The deformation of shear walls due to earthquake loads resembles beam deformation. Shear walls experience overall shear and rotational deformation due to soil deformation. Deformations in moment-resisting frames tend to be almost the same at the top and bottom levels. In buildings that have shear walls, the deformation that occurs is very small at the bottom and large at the top [2].

A steel plate shear wall is a lateral load-resisting system consisting of solid vertical steel plates connecting surrounding beams and columns that are installed along the height of the structure to form a supporting wall [3]. In several studies, it was shown that steel plate shear walls produce large element stiffness, strength, and are very ductile [4]. Therefore, to reduce the earthquake load that occurs adequately, these properties can be utilized. This design also shows that steel plate shear walls are effectively and economically able to withstand wind loads and earthquake loads [5]. By considering the advantages of using steel materials in building structures, the design is designed to use a steel plate shear wall system which functions as a supporting wall for the existing building structure.

LITERATURE REVIEW

Steel plate shear walls have been used for a long time as a system to resist lateral forces from wind loads and earthquake loads. Steel plate shear walls are a lateral load-resisting system consisting of solid vertical steel plates connecting surrounding beams and columns that are installed along the height of the structure to form a supporting wall [4]. Steel plate shear walls have advantages in various ways, for example in cost, ductility, high initial stiffness, fast work process in the field, and also in reducing earthquake loads. The main function of steel plate shear walls is to withstand lateral loads that occur and resist horizontal forces.

Steel plate shear walls are effectively and economically able to withstand wind loads and earthquake loads that occur. These steel plate shear walls are connected to the sides of the beams and columns which work together to withstand earthquake loads and wind loads [6]. In general, horizontal bar walls function as stiffeners [7].

This steel plate shear wall system consists of regular beams and columns that form a portal, connected by infill panels. Steel plate shear walls consist of vertical rods called columns, horizontal rods called beams and thin filler plates that bend in the shear plane and form a diagonal plane to withstand earthquake loads. [8] As shown in figure 1.

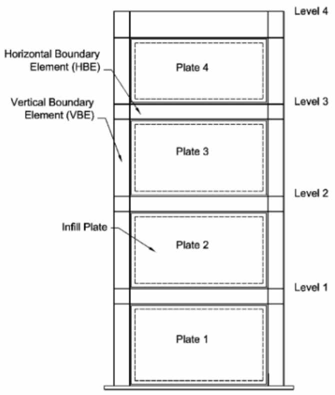

Figure 1. Steel plate shear wall (SPSW)

(Berman and Bruneau, 2004)

Steel plate shear walls are planned and analyzed to determine the strength of the elements in the system, determine the distribution of earthquake shear forces between the shear plate and vertical rods/columns, and calculate the lateral displacement of the rods.

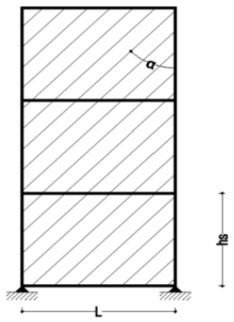

Figure 2. Strip model

(Driver et al, 1998)

The angle of inclination of the vertical bar with the plane of the plate experiencing tension (α) can be calculated using the formula:

$$\alpha = \tan^{-1} \sqrt[4]{\frac{1+\frac{t \cdot L}{2A_c}}{1+t \cdot h_s \cdot \left(\frac{1}{A_b}+\frac{h^3}{360 \cdot I_c \cdot L}\right)}} \quad \text{......(1)}$$

To find out the thickness of the plate, the equation can be used:

$$t_{wi} = \frac{2V_i}{F_y \cdot L \cdot \sin(2\alpha_i)} \quad \text{......(2)}$$

In steel plate shear wall structures there are different shapes and variations, where the dimensions of the shear wall are influenced by the amount of lateral force received by the shear wall. The types of shear wall sections that are common and often used in multi-story buildings are as follows :

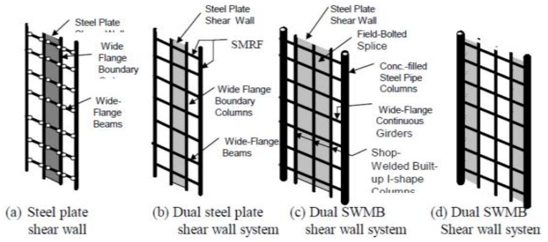

Figure 3. Steel plate shear wall type

METHOD

Designing an earthquake-resistant building structure by adding a steel plate shear wall system aims to determine the strength of the elements in the system, determine the distribution of earthquake shear forces between the shear plates and vertical rods/columns, and calculate the lateral displacement of the rods. To determine the thickness of steel plate shear wall, shear wall beam profile, and shear wall column profile that meets the axial and flexural strength of the building, it is necessary to complete the design stages in accordance with applicable requirements. Starting from data collection, study of literature, preliminary design, load analysis, secondary structure design, SAP 2000 structural modeling and analysis until design control.

Preliminary Design

This preliminary design is the determination of dimensions of the initial structure used. Initial dimensions include the main structure and secondary structure. The design of the earthquake-resistant building structure at Hotel Royal Darmo Yogyakarta includes the main structure: shear beams using IWF profiles, joist beams using IWF, shear columns using Concrete Filled Steel Tube (CFT) and rigid structures using steel plate shear wall.

Loading Analysis

1. Dead Load (Dead load is the weight of all construction materials attached buildings, including walls, floors, roofs, ceilings, stairs, fixed partition walls, finishing, building cladding and architectural components and other structural and other installed service equipment including the weight of the tap. The amount of dead load for buildings are seen in the SNI Regulation).
2. Live Load (Live loads are loads caused by users and occupants of a building or structure other things that do not include construction costs and environmental expenses, such as wind load, rain load, earthquake, and flood load).
3. Wind Load (Wind loads are all loads acting on a building or part of a building caused by differences in air pressure. Loads that take into account the presence of positive and negative pressure acting perpendicular to the planes under consideration. Wind coefficient for closed buildings on external planes, coefficient wind (Kd) = 0.85).
4. Earthquake Load (Earthquake loads are all equivalent static loads that work on a building or part of a building that imitates it the influence of ground movements due to earthquakes. Regulation Earthquake loads are regulated in SNI).

Roof, office floor, and corridor slabs are planned using a bondek plate with a thickness of 0.75 mm. Use useful loads in accordance with provisions of minimum load regulations for building and non-buildings. From the analysis carried out, negative reinforcement values were obtained and the diameter of the reinforcement and the distance between the reinforcements were installed. Results of plate structure calculations this is presented in Table 1.

Table 1. Dimension and Plate Reinforcement

Plate Elements	Useful Load (kg/m^2)	Span (meters)	Plate Thickness (cm)	Negative Reinforcement (cm^2/m)	Reinforcement
Roof	200	2,00	9	1,07	Ø8-250
Office floor	300	2,00	9	1,31	Ø8-250
Corridor	600	2,00	9	2,03	Ø8-200

The function of the joist is to divide/distribute the load from the floor plate to the main beam. The beams are designed to accept dead and live loads only, without being designed to accept lateral loads caused by earthquakes. The results of secondary beam calculations are presented in Table 2.

Table 2. Dimension of Joist

Beam Elements	Profile Type	Deflection (cm)	
		f clearance	f
Roof	WF 450.200.9.14	2,22	0,72
Floor	WF 450.200.9.14	2,22	0,88
Corridor	WF 400.200.8.13	2,22	1,90
Passenger elevator	WF 350.175.7.11	2,08	1,04
Freight elevator	WF 300.150.6,5.9	1,24	0,33

After the load analysis is carried out, a determination can be made for the secondary structure design. The elements designed include stairs, borders, stair stiffeners, beam borders, main beam and support beam which are checked for ultimate moment and deflection. The results of stairs dimensions calculations are presented in Table 3.

Table 3. Stairs Dimensions

Elements	Profile Type	Mu (Kgm)		Deflection (cm)	
		Mu	ØMn	f clearance	f
Stairs	Steel plate (3 mm)	12,42	58,32	0,13	0,05
Borders	Steel plate (3 mm)	10,96	58,32	0,25	0,19
Stair stiffeners	L 45.45.5	65,64	132,30	0,50	0,43
Beam borders	WF 100.50.5.7	78,12	907,20	0,50	0,02
Main beam	WF 250.125.5.8	1848,23	3672	1,23	0,25
Support beam	WF 200.100.5,5.8	2633,62	4320	1,07	0,42

RESULTS AND DISCUSSION

After modeling the 3D structure with the SAP 2000 auxiliary program, the results of the structural analysis must be controlled to certain limits by regulations to determine the suitability of the structural system. The things that must be controlled are mass participation control, control of the structure's vibration period, control of the final value of the spectrum response and control of drift limits. From this analysis, the internal forces that occur in each structural element are also taken to check the cross-sectional capacity.

Mass participation must include a measure of variety combining at least 90% of the actual mass originating from each orthogonal horizontal direction considered. Results of control the value of mass participation this is presented in Table 4.

Table 4. Control The Value of Mass Participation

Output Case	Step Type	Step Number	Sum UX	Sum UY
Text	Text	Unitless	Unitless	Unitless
Modal	Mode	25	0,885	**0,933**
Modal	Mode	26	**0,934**	0,933

From the table above, the mass participation in the X direction is obtained at 93.4% in the 26th mode and mass participation in the Y direction at 93.3% in the 25th mode. So it can be concluded from the structural analysis that what has been done has fulfilled the requirements contained in SNI 1726 : 2012 article 7.9.1, namely mass participation of combined varieties of at least 90%.

For fundamental natural vibration time control is shown in Table 5. the period value is taken in mode 1.

Table 5. Fundamental Natural Vibration Time Control

Output Case	Step Type	Step Number	Period (Sec)	Frequency (Cyc/sec)
Text	Text	Unitless	Unitless	Unitless
Modal	Mode	1	**0,7955**	1,2571
Modal	Mode	2	0,7955	1,2571
Modal	Mode	3	0,7954	1,2573
Modal	Mode	4	0,7954	1,2573
Modal	Mode	5	0,6577	1,5204

The response combination for the dynamic variation basic shear force (Vt) must be 85% greater than the shear force static basis (V) or (V Dynamic ≥ 0.85 V Static). Results of control the end value of spectrum response this is presented in Table 6.

Table 6. Control The End Value of Spectrum Response

Information	V dynamic (kg)	V dynamic ≥ 0,85 Vstatic
RSX	1954231,51	**OK**
RSY	1984292,68	**OK**

The earthquake left multi-story structures vulnerable against the occurrence of horizontal deviation (drift). If this horizontal deviation exceeds the specified safety requirements, the building will experience collapse. Limiting the deviation between floors of a structure has a purpose to prevent non-structural damage and occupant discomfort. Below is presented the control of deviations between floors due to earthquake loads in X direction in Table 7.

Table 7. Control of Deviations between Floors due to Earthquake Loads X Direction

Elevation (meters)	Floor Height (meters)	X Direction Earthquake				Status
		Deviation in the X Direction				
		δei (mm)	δi (mm)	Δ (mm)	Δa (mm)	
36,00	3,50	54,58	327,50	47,80	70	OK
32,50	3,50	46,61	279,70	26,00	70	OK
29,00	3,50	42,29	253,70	24,30	70	OK
25,50	3,50	38,24	229,40	20,70	70	OK
22,00	3,50	34,78	208,70	45,00	70	OK
18,50	3,50	27,29	163,70	23,10	70	OK
15,00	3,50	24,26	145,60	16,70	70	OK
11,50	3,50	21,98	131,90	66,10	70	OK
8,00	3,50	11,97	71,82	24,06	70	OK
4,50	3,50	7,96	47,76	47,76	90	OK
0,00	3,50	0,00	0,00	0,00	70	OK

Below is presented the control of deviations between floors due to earthquake loads in Y direction in Table 8.

Table 8. Control of Deviations between Floors due to Earthquake Loads Y Direction

Elevation (meters)	Floor Height (meters)	Y Direction Earthquake				Status
		Deviation in the Y Direction				
		δei (mm)	δi (mm)	Δ (mm)	Δa (mm)	
36,00	3,50	35,70	214,20	25,00	70	OK
32,50	3,50	31,53	189,20	18,00	70	OK
29,00	3,50	28,54	171,20	40,50	70	OK
25,50	3,50	21,79	130,70	24,50	70	OK
22,00	3,50	17,70	106,20	12,60	70	OK
18,50	3,50	15,60	93,60	15,20	70	OK
15,00	3,50	13,06	78,40	19,50	70	OK
11,50	3,50	9,82	58,90	27,90	70	OK
8,00	3,50	5,17	31,00	9,70	70	OK
4,50	3,50	3,54	21,30	21,30	90	OK
0,00	3,50	0,00	0,00	0,00	70	OK

After controlling the deviation between floors against earthquake loads in the X and Y direction, the dimensions for each main beam and secondary beam structure can be determined according to the available profile. Presented in Table 9 is the calculation of the main structure of the beam elements.

Table 9. Calculation of The Primary Structure of Beams

Elements	Span (meters)	Profile Type	Mu (Kgm)		Deflection (cm)	
			Mu	ØMn	f clearance	f
Main beam	8	WF 800.300.14.26	12116,70	172692	2,22	0,15
Secondary beam	4	WF 450.200.9.14	1614,12	35013,60	1,11	0,05

From controlling the deviation between floors against earthquake loads in the X and Y directions, the dimensions for the column structure can be determined according to the available profile. Presented in Table 10 is the calculation of the main structure of column elements with second order bending moment and axial strength.

Table 10. Calculation of The Primary Structure of Column

Profile Type	Mu (Kgm)		Second Order Bending Moment (Kgm)		Second Order Axial Strength (Kg)		Status
	Mu	ØMn	Mrx	Mry	Pn	Pr	
HSS 800.800.25.25	46295,39	486669,60	113760,54	121039,21	3294375	479837,52	OK

The following is the calculation of steel plate shear walls and their effect on horizontal boundary elements and vertical boundary elements. To design steel plate shear walls, use Unstiffened, thin steel plate shear walls. The results of steel plate shear wall calculations are presented in Table 11.

Table 11. Calculation of Steel Plate Shear Wall

Thickness (mm)	Actual Shear Strength (Kg)		Actual Pull Angle (degree)	Local Buckling Control	Status
	Vu	ØVn	(α)		
4	19125,01	141522,39	38,58°	721,68	OK

After controlling each beam and column structural element, profile determination and lateral buckling control for horizontal boundary element can be carried out. Following are the HBE results in Table 12.

Table 12. Horizontal Boundary Element (HBE) for Shear Wall

Profile Type	Bending Moment (Kgm)		Axial Force (Kg)		Section Control Lateral Buckling (Kgm)		Status
	Mr	Mc	Pr	Pc	Mp	ØMn	
HSS 800.300.14.26	3083,33	176292	207198,13	452004,88	191880	172692	OK

After controlling each beam and column structural element, the profile determination and shear force control for the vertical boundary element can be carried out. Following are the VBE results in Table 13.

Table 13. Vertical Boundary Element (VBE) for Shear Wall

Profile Type	Bending Moment (Kgm)		Axial Force (Kg)		Section Control of Shear Force (Kg)		Status
	Mr	Mc	Pr	Pc	Vu	ØVn	
HSS 800.800.25.25	229628,06	48666960	1087565,83	2964937,50	291525,72	518400	OK

CONCLUSION

This study analyzes earthquake-resistant building structures, namely hotel in Yogyakarta in earthquake-prone areas using a steel plate shear wall system. From the results of the analysis and calculations that have been carried out, economical cross-sectional structural elements are obtained.

By obtaining an economical cross-section that has been obtained presented in the results section, it can be concluded that capacity the cross-section is capable of withstanding the planned loads. Structural analysis modeling uses the SAP 2000 auxiliary program, with four design controls, namely mass participation control, structure vibration period control, spectrum response final value control and drift limit control.

The steel plate shear wall used in the design uses a steel plate shear wall core system. This system is used in medium to high rise buildings such as hotel buildings. Core system type steel plate shear walls provide stiffness against twisting and collapse. Planned and analyzed steel plate shear walls serve to determine the strength of elements in the system, determine the distribution of earthquake shear forces between shear plates and vertical members (columns), and calculate the lateral displacement of the members.

The angle of inclination of the vertical rod to the plane of the plate experiencing tension was found to be 38.58°, which is still in the safe category. To prevent excessive deflection, it is necessary to control the area where the deflection occurs. Deflection or deformation Too much can cause a buckling factor in steel plate shear walls which influences the moment of inertia of the column.

The results obtained from the SAP 2000 program, obtained internal forces such as bending moments and shear forces. This value is then calculated using the formula stated in the regulations regarding steel plate shear wall systems. The calculations obtained for the thickness of the steel plate shear walls, horizontal boundary element (HBE beam), and vertical boundary element (VBE column) are still in the safe category.

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