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A Shear Wall Design Study in an 8-Story Building

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Abstract. Indonesia is an earthquake-prone region. These natural disasters have caused buildings to collapse and claimed many lives, highlighting the need for earthquake-resistant design. Faculty of Engineering (FE) of Universitas Sriwijaya plan to build an earthquake-resistant 8-story building functioning as classrooms and office. The problem is how to determine the appropriate structural system between SMRF alone or a combined SMRF-SRCSW system and how to determine the optimal position of the shear wall without disturbing the existing layout in the FE Tower.
This research method employed a simulation experiment using six models of FE Tower. The Model was analyzed using software to obtain fundamental vibration period, mode shape, soft story check, torsional irregularity check, and the concrete structure design analysis.
Software analysis results indicate that the FE Tower exhibits both vertical and horizontal geometric irregularities, necessitating dilatation for simplification. The structural system used in this design combines SMRF and SRCSW, and the optimal position of the shear wall is positioned on the outer wall and corner of the building.

Keywords: shear wall, vibration period, mode shape, soft story, torsion

1. Introduction

Indonesia is known as an earthquake-prone region. There have been many major earthquakes in Indonesia such as the Aceh earthquake in 2004, the Yogyakarta earthquake in 2006, the Padang earthquake in 2009 and the Lombok and Palu earthquakes in 2018. Many buildings and infrastructure suffered damage, and the disasters took casualties due to the collapse of the building. With these conditions, buildings built in Indonesia must be resistant to earthquakes.

A building resistance system to earthquake can be done actively and passively (Mungase et al., 2024). The active resistance is based on the strength and rigidity of the structure such as structure frame, shear wall, floor diaphragm, joints and materials. The passive resistance, on the other hand, relies on mechanical or electronic equipment like base insulators and dampers to reduce earthquake dynamic vibrations towards structures.

The Faculty of Engineering (FE) at Universitas Sriwijaya plans to construct an 8-story building named FE Tower that will function as classrooms and office building (figure 1.1) to accommodate the academic and administration activities. The ground floor will be used for the parking lot, the 1st floor and the 7th floor will function as public facilities, the 2nd floor will be utilized as offices and faculty administration, the 3rd floor will serve as classrooms, and the 4th floor and the 6th floor will be used for administration rooms for departments and study programs. The layout and form of the building are designed based on the needs of space, site shape and aesthetics. 8-story buildings are already considered high-rise buildings, which means that lateral loads (earthquake loads and wind loads) will be dominant. In Indonesia, the building resistance system to lateral loads applied uses active resistance with reinforced concrete materials. There are two structural systems of reinforced concrete, namely the concrete frame and the combination of concrete frame and shear wall.

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The advantage of using shear walls lies in its very high rigidity (Arum et al., 2015) which is perfectly suitable in resisting the earthquake force. However, if the shear wall is positioned in an FE Tower without careful planning, it may cause excessive torsion (Satheesh et al., 2018) and damage the existing layout. Therefore, the research simulation experiments with 6 models will be conducted to prevent these problems; and the analysis of the fundamental vibration period, mode shape, soft story check, torsional irregularity check and concrete structure design will be conducted to obtain the appropriate structural system and the optimum position of the shear wall in the FE Tower.

Figure 1.1. The block plan and FE Tower perspective (source, Year)

2. Methods

2.1. Simulation Experiment

The research employed a simulation experiment to test the regularity of the building model so that it can meet the criteria for earthquake-resistant buildings.
This simulation experiment used STAAD PRO Connect 2023 software. Model regularity checking was limited to the irregularities that frequently occur and have the most damaging impact; namely soft story and torsional irregularity (FEMA, 2020). In this study, the purpose of checking the fundamental vibration period (T) of each building model is to determine the rigidity of its geometry, the purpose of checking the mode shape is to determine the regularity of the building geometry, and the purpose of checking the structural system SMRF or the combined SMRF (Special Moment Resisting Frame) and SRCSW (Special Reinforced Concrete Shear Wall) to determine the structural strength of FE Tower.

Table 2.1. Structure properties of model 01-06

Models	Beam dimension (cm)	Column dimension (cm)	Floor plate thickness (cm)	Shear wall thickness (cm)	Concrete grade (Kg / cm2)	Reinforcement grade (Kg / cm2)	Stirrup grade (Kg / cm2)
01	25x40, 25x50	80x80, 70x70	12	-	300	4200	4200
02	25x40, 25x50	80x80, 70x70	12	-	300	4200	4200
03-06	25x40, 25x50	80x80, 70x70	12	25	300	4200	4200

There are 6 models (figure 2.1), and they have structure properties in Table 2.1 as the software input. Model 01 is the full geometry of the FE Tower plan with SMRF structural system. In model 02, the north wing of the building is dilated from the main building and the structural system is still SMRF. Model 03-06 is the model of shear wall positioning plan with the combined structural system of SMRF and SRCSW.

The models were then analyzed using software to obtain fundamental vibration period, mode shape, soft story check, torsional irregularity check and concrete structure design analysis.

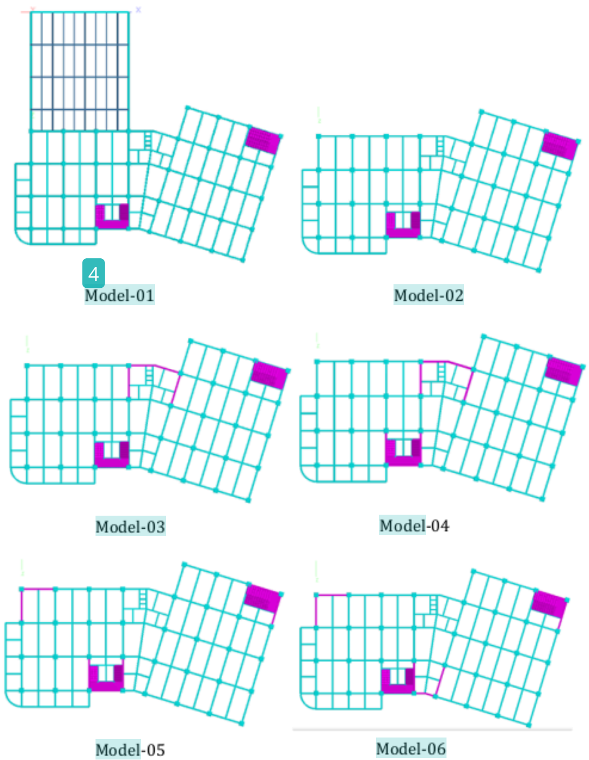

Figure 2.1. The simulation experiment model plan

2.2. Irregularities of Building Geometry

The irregular geometry of the building will affect the resistance of the building to earthquakes. When a large earthquake hits, buildings with irregular geometry tend to experience more severe damage than the ones with regular geometry (Harmankaya & Soyluk, 2012). To determine the geometrical irregularity of a building there are two evaluation criteria: horizontal geometric irregularities and vertical geometric irregularities (BSN, 2019). The horizontal geometric irregularities consist of: Torsional irregularity, Re-entrant Corner Irregularity, Diaphragm Discontinuity Irregularity, Out of Plane Offsets Irregularity, and Nonparallel Systems Irregularity; while the vertical geometric irregularities comprise of Stiffness (Soft Story) Irregularity, Weight (Mass) Irregularity, Vertical Geometric (setback) Irregularity, In-Plane Discontinuity Irregularity, and Strength (Weak Story) Irregularity.

2.3. Positioning of Shear Walls

Shear walls serve multiple functions, including resisting shear forces (BSN, 2019), mitigating torsion caused by the eccentricity of the mass center and the rigidity center (Batu et al., 2016), enhancing rigidity and reducing deformation (Kewalramani & Syed, 2018), and reducing soft story effects (Ujwal et al., 2024).

The efficiency and optimization of shear walls depend on their positioning. If they are not properly positioned, it will increase the existing eccentricity (Banerjee & Srivastava, 2020). Regarding shear walls positioning, some experts suggest the trial and error method (Banerjee & Srivastava, 2020; Kewalramani & Syed, 2018; Powale & Pathak, 2019). Furthermore, the research of Andalas et. al. (Andalas & Riakara Husni, 2016) argues that the most optimal position of shear walls is at the outer wall because they can increase the inertia rigidity of the building.

2.4. Modal Analysis

Period (T) is the period of fundamental vibration of a building, and it is used to measure the building's structure rigidity (Budiono & Supriatna, 2011). If the building has a period (T) < Tmax, the structure is considered rigid while if it has a period (T) > Tmax, the structure is considered flexible. Tmax is the maximum period of vibration allowed to occur in a building.

Mode shapes (Ux, Uy and Rz) are the deformation of the structure when they vibrate at their natural frequency. Mode shapes can be used as an initial indication in assessing the degree of building irregularities. A building, with mode 1=translation of the X or Y axis direction, mode 2=translation of the Y or X axis direction and mode 3=rotation of the Z axis direction, is indicated to have relatively regular geometry (Chopra, 2001; Kartiko et al., 2021; Murty et al., 2012; Putri et al., 2021). Modes 1, 2 and 3 have values between 0-1, so If the value approaches 1, it means translational or rotational dominance and vice versa.

2.5. Structural system of SMRF and SRCSW

In Indonesia, where earthquakes frequently occur, SMRF and SRCSW are the most commonly used structures

According to SNI 1726: 2019 (BSN, 2019), the SMRF structural system has factors R=8, Ωo=3 and Cd=5.5. On the other hand, the combined structural system of SMRF and SRCSW has factors R=7, Ωo=2.5 and Cd=5.5 and must meet the criteria of SMRF where it must able to resist at least 25% of seismic forces while the remaining 75% is resisted by SRCSW.

3. Discussion

3.1. Fundamental Vibration Period (T)

Chart 3.1. Fundamental Vibration Period (T) of Models 01-06

Models	Ta	Tmax	T (seconds)	
	(seconds)	(seconds)	X	Y
Model-01	1.304	1.825	2.099	2.009
Model-02	1.304	1.825	2.208	2.179
Model-03	0.783	1.097	1.441	1.153
Model-04	0.783	1.097	0.800	0.877
Model-05	0.783	1.097	0.902	0.855
Model-06	0.783	1.097	0.980	0.874

Ta and Tmax are the minimum and maximum limits of the fundamental vibration period based on SNI code 1726:2019 (BSN, 2019) while T is the fundamental vibration period of the model obtained from software analysis results. Table 3.1 shows the Model 01 and 02 had fundamental vibration period (T) > Tmax which means both models are flexible enough to require additional rigidity. After adding shear walls in the center of the building, specifically at the upper part the plan, model 03 was still T > Tmax which, hence still needing additional shear walls. After adding shear walls at the top and bottom of the plan, models 04-06, finally T < Tmax was reached, which means these models have already a fairly good rigidity compared to other models.

3.2. Mode Shape

Model 01, model 05, and model 06 have dominant mode shapes, namely mode 1 and mode 2 translation whereas mode 3 rotation indicates the building geometry is relatively regular. For model 02 and model 03, mode 1 and mode 3 rotation are dominant while mode 2 translation indicates irregular building geometry. For model 04, furthermore, mode 1 rotation is dominant while mode 2 and mode 3 translation indicate that the FE Tower geometry is irregular, so it should be avoided (table 3.2). Thus, model 01, model 05 and model 06 are the best models based on mode shapes.

Table 3.2. Mode Shape Ux, Uy and Uz, Model 01-06

Models	**Mode 1**		**Mode 2**		**Mode 3**	
	Ux (%)	Uy (%)	Ux (%)	Uy (%)	Ux (%)	Uy (%)
Model-01	59.63	0.26	0.79	66.33	8.27	1.55
Model-02	6.47	46.22	68.68	5.11	0.09	23.65
Model-03	26.58	1.8	3.49	63.24	38.45	1.55
Model-04	18.52	0.68	0.03	64.44	50.5	0.53
Model-05	62.79	1.72	1.88	63.69	2.43	0.13
Model-06	57.84	4.11	5.24	59.95	4	1.64

3.3. Soft Story Check

Table 3.3. Column Slenderness Criteria

Lateral element type	**Requirements**	
Columns	Net column height/column dimension; h0/D	Definition of h0/D
a). Slender	6°h0/D	
b). Normal	2<h0 / D<6	
c). Short	h0 / D2	

One potential occurrence of a soft story is the existence of different column heights (Pesaralanka et al., 2023; Ulutas, 2024). This problem can be seen in the FE Tower plan. In model 01, the height from the ground floor to 1st floor (elev. 3 meters) is 3 meters; the height from some parts of the 1st floor to the 2nd floor (elev. 7 meters) is 4 meters; the height from the 2nd floor to 3rd floor (elev. 9 meters) is 2 meters; the height of some parts of the of the 1st floor (elev. 3 meters) to the 3rd floor (elev. 9 meters) is 6 meters; and the height from the 3rd floor to roof top floor that has height 4 meters. In model 02-06, after the north wing of the building was dilated from the main building, there are some changes in the building height. These changes are described as follows the height from the ground floor to the 1st floor (elev. 3 meters) is 3 meters, the height from the 1st floor to the 3rd floor (elev. 9 meters) is 6 meters, the height from the 3rd floor to 4th floor elevation (elev. 13 meters) is 4 meters, and the height from the next column up to the roof top floor is 4 meters.

For this case, the preliminary dimension of the column suggested by Seki (Seki & Islam, 2015)and Okada (Okada Et Al., 2005) was conducted to avoid the potential occurrence of the soft story with the rules in Table 3.3.

Where h0=the net height of the column per floor after subtracting the beam height and D=the reviewed column dimensions. Based on the normal column rule (2<h0/D<6), the column dimension of the ground floor to the 4th floor is 80x80 cm while the column dimension of the 4th floor to the roof top floor is 70x70.

The result of checking the soft story (table 3.4) shows if the building is full model (model 1) with different column heights and without dilatation, there is a soft story in the column between +3 meters and +7 meters elevation. However, after dilatation (model 02-06), the soft story can be removed, which means the column dimensions are strong enough to reduce the potential effect of the soft story, and it can be concluded that the model 02-06 are good models without a soft story.

Table 3.4. Checking Soft Story Model 01-06

Floor	Model01	Model02	Model03	Model04	Model05	Model06
elev. 3 meters	OK	OK	OK	OK	OK	OK
elev. 7 meters	Soft	-	-	-	-	-
elev. 9 meters	OK	OK	OK	OK	OK	OK
elev. 13 meters	OK	OK	OK	OK	OK	OK
elev. 17 meters	OK	OK	OK	OK	OK	OK
elev. 21 meters	OK	OK	OK	OK	OK	OK
elev. 25 meters	OK	OK	OK	OK	OK	OK
elev. 29 meters	OK	OK	OK	OK	OK	OK
elev. 33 meters	OK	OK	OK	OK	OK	OK
elev. 37 meters	OK	OK	OK	OK	OK	OK

3.4. Torsional Irregularity Check

Table 3.5. Checking Torsional Irregularity Model 01-06

Floor	Model01	Model02	Model03	Model04	Model05	Model06
elev. 3 meters	OK	OK	Extreme	Extreme	Failed	OK
elev. 7 meters	Extreme	-	-	-	-	-

elev. 9 meters	Failed	OK	Extreme	Extreme	OK	OK
elev. 13 meters	OK	OK	Extreme	Failed	OK	OK
elev. 17 meters	OK	OK	Extreme	Failed	OK	OK
elev. 21 meters	OK	OK	Extreme	Failed	OK	OK
elev. 25 meters	OK	OK	Extreme	Failed	OK	OK
elev. 29 meters	OK	OK	Extreme	Failed	OK	OK
elev. 33 meters	OK	OK	Extreme	Failed	OK	OK
elev. 37 meters	Extreme	Extreme	Extreme	Extreme	Failed	Failed

As shown in Table 3.5, the full model buildings condition (model 01) experienced excessive torsion (Extreme) at 7-meter elevation and 37-meter elevation (at the roof floor). After dilatation, model 02 only experienced excessive torsion (Extreme) on the roof floor. In models 03 and 04, there was still wrong positioning causing torsion (Failed) and excessive torsion (Extreme). Model 05 has improved torsion behavior though torsion still occurs at the 3-meter floor elevation and at the roof top floor (elev. 37 meters). The last model, model 06, the position of the shear wall is correct but there is still torsion on the roof floor. This is due to the ununiform distributed load (load ME and ornamental elements of *tanjak*) and there are large roof voids needing special treatment. When compared to all models in this category, models 02 and 06 are the best ones since they experienced the least occurrence of torsional irregularities.

3.5. Structure System

Based on the vibration period checking (T) of each model, the model with shear walls on the outer wall and at the building corners (model 04-06) has good rigidity. Based on the mode shape, both complex models (model 1) and simplified models with dilatation (model 05 and 06) can have regular building criteria though the torsion potential must be rechecked. For the soft story category, it can be removed after dilatation (model 02-06). Finally, based on torsion checking, only model 02 (without shear wall) and 06 (with shear wall) experience the least occurrence of torsional irregularities.

Furthermore, to ascertain whether the FE Tower requires shear walls or not, a concrete structure design analysis with a combination of gravity load and lateral load was performed on model 02. The results then show that most of the column and beam structural elements have experienced design failures. Therefore, this building requires other structural elements to resist lateral forces, namely shear walls and balanced position like model 06.

It can be concluded that the FE Tower requires a combination of SMRF and SRCSW structures to increase its rigidity and improve its deformation behavior to be relatively regular.

4. Conclusion

Based on the analysis of the vibration period, mode shape, soft story check, torsional irregularity check, and concrete structure design analysis above, it can be concluded that:

- The irregularity of FE Tower can be solved by conducting by dilatation and applying of the SMRF and SRCSW combined structural system.

- The optimum shear wall position is on the outer wall and in the corners of the building (model 6), where the position is strong enough to provide rigidity, and it relatively does not disturb with the existing layout of the FE Tower.

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