Response analysis of a multi-story building structure with a variety of horizontal irregularities and shear wall geometries

A H Prathama¹, M Teguh¹, and F Saleh²
¹ Department of Civil Engineering, Islamic University of Indonesia Indonesia
² Department of Civil Engineering, Muhammadiyah University of Yogyakarta
Email: m.teguh@uii.ac.id

Abstract. The growing growth of human activities has led to changes in housing patterns in urban areas. The land crisis in urban areas has made land prices uneconomical, so buildings are designed vertically. One solution to resist earthquakes in multi-story buildings is to add a shear wall structure with the proper profile and layout. Shear wall designs with variations influence the base shear, drift ratio, lateral deflection, and story drift patterns. This study presents the structural response comparison of buildings against variations in the profile and layout of shear walls subjected to earthquake loads. Force Based Design method utilizing the response spectrum approach was adopted in the analysis and carried out using SAP200. Six structural models comprise a frame without shear walls, three L-profile shear walls, two I-profile (straight) shear walls. The simulation results of the overall structural models show that the profile and layout configuration of shear walls in the frame structure of a multi-story building correlates directly to the performance of base shear, drift ratio, and story drift with relatively comparative conditions.

1. Introduction
Indonesia is located between the Eurasian, Indo-Australian, Pacific, and Philippine plates. In addition, Indonesia is also found in the Pacific Ring of Fire which causes frequent earthquake activities. This geological condition causes the high movement of tectonic earthquakes in Indonesia [1-3]. On the other hand, population growth is increasing, causing changes in the pattern of housing development in urban areas in a vertical direction, such as high-rise buildings according to their needs [12, 16]. The land crisis in urban areas has resulted in costly land prices, so facilities are designed vertically as a solution and considered an alternative for adequate human activity growth [4-5]. The new trend in building housing in urban areas is to develop the design concept of earthquake-resistant high-rise buildings [13, 18]. In designing irregular building structures in earthquake-prone areas, accuracy in the profile and layout of shear walls is essential to reduce the potential risk of damage due to future earthquake forces [19]. A multi-story building construction needs to consider various aspects of the structure to meet standard requirements [11, 14-15]. The profile and layout of the shear walls that are right on target can reduce the story drift in the building structure and increase the rigidity of the building, thus contributing to the occurrence of torsion in the building [6-9]. Lateral loads cause torsion on structures when the loads tend to rotate the building either vertically or horizontally. The torsion occurs when the center of gravity load does not match the center of stiffness, producing the significant eccentricity of the torsional moment during an earthquake event that directly affects the structure's resistance system. This torque increases lateral deflection at extreme building points and causes problems with lateral retaining elements located on the edge of the building [10].
Researches on variations in the profile and layout of shear walls in buildings were studies by previous researchers considering the effect of the base shear and drift ratio [20]. Each variation was simulated to determine the most effective shear wall position in resisting these forces. Shear walls installed on the outside of a building could withstand greater lateral forces than shear walls installed on the inside of the building as the core of the building or vice versa [8]. In this study, various shear walls, such as L and I-profiles, are allocated in and outside. The results include the base shear, drift ratio, lateral deflection, and the story drift pattern of the shear wall's position and configuration in the building compared to determine the structural response.

2. Theoretical Basis

2.1 Structural Irregularity

Building structures can be classified as irregularity or structural order based on SNI 1726-2019 clause 7.3.3. The classification must be based on horizontal and vertical configurations following SNI 1726-2019 Table 13 and SNI 1726-2019 Table 14. The characteristics of horizontal irregularity are as follows.

1. Torsion irregularity (1a and 1b)

The torsion irregularity 1a is defined to exist if the story drift between the maximum levels, which is calculated including the torsion unpredictable with $A_x = 1.0$, at one end of the structure transverse to an axis is more than 1.2 times the story drift between the mean levels at both ends of the system. The torsion irregularity requirement in the reference articles applies only to structures in which the diaphragm is rigid or semi-rigid. The torsional irregularity 1a is formulated as follows.

$$1.2\delta_{avg} \leq \delta_{max} \leq 1.4\delta_{avg}$$ (1)

Transverse to an axis at one end of the structure is more than 1.4 times the mean inter-story drift at both ends of the system. The excess of torsion irregularity requirement in the reference articles applies only to facilities in which the diaphragm is rigid and semi-rigid [10]. The torsion irregularity 1b is formulated as follows.

$$\delta_{max} \geq 1.4\delta_{avg}$$ (2)

2. Re-entrant Corner Irregularity

The defined re-entrant corner irregularity exists if the two dimensions of the structure plan projection from the inner corner location are greater than 15% of the dimension of the structure plan in the direction under consideration. Therefore, re-entrant corner irregularity can be formulated as follows.

$$P_y > 0.15L_y \text{ and } P_x > 0.15L_x$$ (3)

3. Irregularity of diaphragm discontinuity

A diaphragm discontinuity is defined as an existing diaphragm having discontinuity or sudden stiffness variations [15]. This condition includes a cut or open area greater than 50% of the gross diaphragm area closed or a change in effective diaphragm stiffness by more than 50% from one level to the next.

The characteristics of vertical irregularity are as follows.

a. Weight irregularity

Weight irregularity occurs when the effective mass of any level is more than 150% of the effective mass at adjacent levels. However, according to SNI 1726: 2019 clause 7.3.2.2 [17], the weight irregularity does not comply if there is no story drift ratio between levels due to the design lateral seismic force is significantly higher than 130% of the story drift ratio between levels above it.

b. Vertical geometric irregularity

This irregularity exists when the dimensions of the lateral load-bearing system at any level are more than 130% of the measurements at any adjacent level.
c. Weak story irregularities due to discontinuities in the lateral strength of the story
The irregularity occurs when the holding part's shift (offset) is greater than the component width. Alternatively, there is a reduction in the stiffness of the holding element at the low level.

2.2 Design Response Spectrum
The design response spectrum should be developed following the conditions.

For periods less than \( T_0 \) and less than or equal to \( T_s \), the design acceleration response spectrum, \( S_a \), equals to \( SDS \), must be taken from the following equation:

\[
S_a = SDS \left( 0.4 + 0.6 \frac{T}{T_0} \right)
\]  

(4)

For periods greater than or equal to \( T_0 \) and less than or equal to \( T_s \), the acceleration response spectrum of \( S_a \) design equals \( SDS \).

\( S_a \)'s design acceleration spectral response is based on the following equation for periods greater than or equal to \( T_0 \) but less than or equals \( T_L \):

\[
S_a = \frac{SD}{T}
\]  

(5)

\( S_a \)'s design acceleration spectral response is based on the following equation for periods greater than or equal to \( T_s \) but less than or equals \( T_L \):

\[
S_a = \frac{(SD_1 \times T_L)}{T^2}
\]  

(6)

2.3 Base Shear Seismic
According to the following equation, the seismic-based shear force (\( v \)) in the specified direction shall be determined.

\[
V = C_s \times W
\]  

(7)

\[
C_s = \frac{SDS}{(R/I_e)}
\]  

(8)

According to Eq. (8), the value of \( C_s \) calculated does not need to exceed the following equation.

For \( T \leq T_L \)

\[
C_s = \frac{SD}{T(R/I_e)}
\]  

(9)

For \( T > T_L \)

\[
C_s = \frac{(SD_1 \times T_L)}{(T^2 (R/I_e))}
\]  

(10)

\( C_s \) must be not less than

\[
C_s = 0.044SDS \times I_e \geq 0.01
\]  

(11)

For structures located in areas where \( S_I \) is equal to or greater than 0.6g, the \( C_s \) must be not less than:

\[
C_s = \frac{0.5 \times S_I}{(R/I_e)}
\]  

(12)

2.4 Story Drift
According to SNI 1726: 2019 article 7.8.6, the story drifts between the design levels (\( \Delta \)) must be considered the mass center variation above and below the reviewed level. Suppose the center of mass is not aligned in the vertical direction; the story drift at the base of the level is then based on the vertical projection of the center of mass above it. The centroid nonconformity at the -x (\( \delta_x \)) level should be determined accordingly using the following equation:

\[
\delta_x = \frac{c_g \delta_{xe}}{I_e}
\]  

(13)
4

\[ DR = \left( \frac{y_I - y_{(i-1)}}{H} \right) \times 100 \]  

(14)

3. Analysis Method

This study compares the performance of horizontal irregular buildings with shear walls using the form and layouts of shear walls by design.

3.1 Structural Model

The structural model used for the research object is a reinforced concrete frame structure with irregular interior angles—the number of system levels with 15 floors and each height level of 3 meters. The shear wall layout simulation determines the shear wall's contribution to the base shear force, drift ratio, lateral deflection, and story drift patterns caused by variations in shear wall layout [1, 3-4].

| No | Parameter                  | Description               |
|----|----------------------------|---------------------------|
| 1  | Building function          | Apartment                 |
| 2  | The building location      | Yogyakarta                |
| 3  | Subgrade type              | Soft soil                 |
| 4  | Number of stories          | 15 Stories                |
| 5  | height between floors      | 3 m                       |
| 6  | Building height            | 45 m                      |
| 7  | The length of the building in the x-direction | 44 m |
| 8  | The length of the building in the y-direction | 38 m |
| 9  | Area of building           | 1672 m²                   |
| 10 | Structural type            | RC structure              |
| 11 | Structural system          | Dual system               |
| 12 | Compressive strength of concrete for the slab | 25 MPa |
| 13 | Compressive strength of concrete for the beam and column | 30 MPa |
| 14 | Yield strength of reinforcing steel with Ø ≤ 12 mm | 280 MPa |
| 15 | Yield strength of reinforcing steel with Ø > 12 mm | 420 MPa |

The building data used in this study is depicted in detail in Table 1, and the shear wall configuration for five proposed models is outlined in Figures 1-5. This study uses five models with the following structure as listed in Table 2.

| Model | Type       | Frame configuration                     | Model description |
|-------|------------|----------------------------------------|-------------------|
| 1     | L-Profile  | A1-A3 & A1-C1, H4-H5 & G5-H5          | Figure 1          |
| 2     | I-Profile  | A1-A3 & H1-H3                          | Figure 2          |
|       | (straight) |                                        |                   |
| 3     | L-Profile  | A1-A3 & A1-C1, D6-D8 & B8-D8          | Figure 3          |
|       | (straight) |                                        |                   |
| 4     | I-Profile  | A1-C1 & A8-C8                          | Figure 4          |
|       | (straight) |                                        |                   |
| 5     | L-Profile  | A1-A3 & A1-B1, G1-H1 & H1-H3, H4-H5 & G5-H5 | Figure 5          |
3.2 Research Methods
The method used in this research is the Force Based Design (FBD) method considering the static equivalent and response spectrum approach. Figures 1-5 show that the model variations consist of buildings without shear walls, straight-profile shear walls, and L-profile shear walls.
4. Results and Discussion

4.1 Base Shear

The base shear generated in the equivalent static analysis ($V$) and the combined response ($V_t$) analysis is shown in Figure 6. Model 1, Model 3, and Model 5 demonstrate higher base shear forces compared to three other models.

![Figure 6. Base shear](image)

4.2 Lateral deflection

The lateral deflection comparisons resulting from differences in building structure models are presented in Figures 7 and 8. This study shows six structural models: a frame without shear walls (original model), three $L$-profile shear walls, and two $I$-profile (straight) shear walls.

The resulting lateral deflections based on the analysis in the SAP2000 application above shows that the lateral deflection generated in structural modeling using shear walls reduces lateral deflection by a significant percentage to help the building designers minimize structural failures in buildings. The result of the optimal lateral deflection in each shear wall modeling in the $x$-direction is the shear wall structure Model 4 and the shear wall structure Model 5. In contrast, the optimal result for the $y$-direction is the shear wall structure Model 5. The results are excellent and optimum because they have the most significant difference in strength than structures without shear walls (original model).

![Figure 7. Lateral deflection in the $x$-direction](image)

![Figure 8. Lateral deflections in the $y$-direction](image)

4.3 Drift ratio

The drift ratio comparison due to differences in building structure models is depicted in Figures 9 and 10. The greater the drift ratio value in a building structure, the more flexible/less rigid the building structure is. The drift ratio in a building structure is small, which means that the building structure is more stringent. For example, the provision of shear walls in a building plan can reduce the value of the lateral deflection that occurs on each floor of the building.

The maximum drift ratio of 20.67% achieved in the practical matter in the $x$-direction is the shear wall structure Model 4. On the other hand, the most effective drift ratio of 22.67% is achieved by the shear wall structure Model 5.
In the graph of the story drift between floors and the drift ratio graph, it can be seen that the shear wall Models 1, 3, 4, and 5 produce a more negligible lateral deflection between floors than the model without shear walls at the points viewed in the x-direction or those considered in the y-direction. On the other hand, a different condition has been experienced in the x-direction of Model 2, where this model has less strength than others. Thus, the structure indicates that the shear wall layout variable produces smaller lateral deflections or is better in resisting lateral forces due to earthquakes when compared to other models without shear walls.

### 4.4 Story Drift

The results of the story drift between floors on various types of shear wall models have different effects. The results of the story drift between levels are lesser in the axis where the shear wall layout is in that axis. Figures 11-12 show a comparison of story drift between floors due to differences in building structure models.

The shear wall structure Model 5 focuses on the parameters of the story drift between floors, with a relatively minor story drift compared to other models. The shear wall structure shows that Model 2 more dominantly reduces the story drift between floors in the y-direction. On the other hand, the shear wall structure Model 4 dominantly lessens the divergence between floors in the x-direction. Figures 11 and 12 show that the shear wall structure Model 5 has the most optimum profile and layout. The shear wall structure Model 5 has an L-Profile shear wall with the shear walls at each corner of the building in the longitudinal direction.
From the 1st to the 3rd floor, the structure without a shear wall produces significant story drifts compared to the floors above it. This condition is because that floor has a far drift eccentricity range between the center of mass and stiffness above. In contrast, structures without shear walls have the largest story drift due to the stiffness is relatively smaller than other shear wall model structures, or vice versa. These results indicate that the building is insufficiently rigid at lower stiffness but may increase the story drift.

5. Concluding Remarks
The conclusions that can be drawn based on the analysis results of five variations in the profile and layout of shear walls are as follows:

1) The base shear forces generated from modeling the building structure are the most significant force of 40,175 kN achieved by Model 5.
2) The proposed five structural models provide relatively small lateral deflections in the x-direction, except Model 2 tends to close the original model (without shear walls), producing higher values. However, this model in the y-direction has achieved more significant lateral deflections.
3) The maximum drift ratio experienced in the practical matter in the x-direction is Model 4 of 20.67%, but the most effective drift ratio is reached by Model 5, with 22.67%.
4) Four of the five proposed models produce story drifts close to the allowable limits. Still, they have excessive the limit state, while Model 2 and the original model are relatively weak contributing story drifts that far exceed the permissible story drifts. The last two models are the lowest structural response behavior occurred in the x-direction. In contrast, Model 2 in the y-direction is much more robust in resisting lateral forces than the other models, contributing to story drift beyond the allowable limit.
5) The proportion of shear walls with a more excellent value is reached by increasing the layout of shear walls in the appropriate building design. It is evidenced in the shear wall structural modeling Model 5 has an average ratio of the x-direction of 39.05% and the y-direction of 41.68%.

References
[1] H Manalip, E J, Kumaat, F I Runtu 2015 Layout of Shear Walls in Reinforced Concrete Buildings With Pushover Analysis, Media Engineering Scientific Journal Vol. 5 No.1, Universitas Sam Ratulangi, Manado
[2] S Kemberly, R S Windah, and B D Handono 2018 Response of Multi-storey Building Structure with Variation of Column Stiffness due to Earthquake Based on SNI 03-1726-2012 Civil Static Journal, Vol.6, No.6, Universitas Sam Ratulangi, Manado.
[3] G Andalas, Suyadi, H R Husni 2016 Shear wall Layout Analysis on Building Structure Behavior Journal of Civil Engineering Department, Faculty of Engineering, Universitas Lampung.
[4] F Effendi, W Wesli, Y Chandra, S J Akbar 2018 Study of Shear Wall Layout Against Natural Vibration Time Fundamentals of Building Structures. Teras Jurnal, 7(2), 274, , Universitas Malikussaleh, Aceh.
[5] M L Batu, B Servie, S O Dapas, SE Wallah 2016 The efficiency of Using Sliding Walls to Reduce Torque Effects in Irregular Building. Civil Static Journal, January, 4(1), 29–35, Universitas Sam Ratulangi, Manado,
[6] L Fauziah, M D J Sumajouw, S O Dapas, R S Windah 2013 Effect of shear wall layout and position on the deviation of multi-story reinforced concrete buildings due to earthquake loads, Civil Static Journal, Vol,1 No,7 Juni 2013 (466-472), Universitas Sam Ratulangi, Manado,
[7] A Kurnia, S H Dewi, M Kurniawan 2018 Effect of Shear Wall Position on Structure Performance in Irregular Buildings Using Response Spectrum Method, Scientific Journal, Vol.18, Nomor 1, Universitas Islam Riau, Riau.
[8] B O Majore, S E Wallah, S O Dapas 2015 Comparative study of the dynamic response of multi-storey buildings with variations in shear wall layout. Civil Static Journal, Vol,3 No,6 Juni 2015 (435-446), Universitas Sam Ratulangi, Manado.
[9] W Ahmad, Rizwanullah 2017 Comparative analysis of an irregular structure with and without shear wall frame system, *the International research journal of engineering and technology (IRJET)*, Volume 4, issue 07, Al-Falah University, India.

[10] N K Astariani 2010 Torque effect on building, *Ganec Swara, Special edition Vol,4 No,3*, Faculty of Engineering, Universitas Ngurah Rai Denpasar, Denpasar.

[11] A A Mondal, G B Bhaskar, D Telang 2017 Comparing the effect of Earthquake on Shear Wall Building and Non-Shear Wall Building – A Review, *International research journal of engineering and technology (IRJET)*, India.

[12] Hyundai Elevator 2015 *Planning Guide Hyundai Elevator*: C-EPG-E1705.Korea.

[13] I Iswandi, H Fajar 2016 Advanced Design of Reinforced Concrete Structures, ITB Press, Bandung.

[14] G S Krishna, S Chaithra 2017 Comparative Study of Frame Shear wall Building With Different Opening Configurations, *International Journal of Advance Engineering and Research Development*, Sree Narayana Institute of Technology, Kerala.

[15] M D P Putra 2018 Comparison of Horizontal "L" Shaped Irregular Building Structures Against Conditions of Rigid Floor and Flexure Floor Systems, and Sliding Wall Systems, *Final project*, Universitas Muhammadiyah Sumatera Utara, Medan.

[16] PPURG 1987 *Loading Design Guidelines for Houses and Buildings*, Publishing Agency Foundation, PU, Jakarta.

[17] Standar Nasional Indonesia 2019 *Procedures for design earthquake resistance for building and non-building structures*, SNI 1726, Jakarta.

[18] Standar Nasional Indonesia 2013 *Structural concrete requirements for buildings and explanations*, SNI 2847, Jakarta.

[19] Standar Nasional Indonesia 2013 *Minimum load for designing buildings and other structures*, SNI 1727, Jakarta.

[20] V Suwalka, N Laata, B Nagar 2018 Comparative Study and Modelling of Framed Structure with Shear Wall & Without Shear Wall by Using ETABS, *International research journal of engineering and technology (IRJET)*, Vol.5, Jagannath Gupta Institute of Engineering and Technology, India.