Seismic assessment of irregularities in steel special moment resisting frame with asymmetric-plan building (case study: Gedung D – Universitas Dharma Andalas)

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Abstract. The limitation of land is becoming the issue where the symmetric-plan building could not always be the proper choice. Besides that, the demands of architectural and esthetical construction also quickly increase. Then, there is the possibility where asymmetric-plan building will be the choice, in this case Gedung-D Universitas Dharma Andalas. But, designing asymmetric-plan building is having obstacle where the past studies revealed that the damage under strong ground motion become the major problem. It is because the asymmetric-plan will lead excessive torsion due to the horizontal irregularities or soft-story issue due to vertical irregularities. Then, it certainly affects the stability of structure. This research conducted the seismic assessment of asymmetric-plan 5-story building where Gedung-D Universitas Dharma Andalas, Padang will take place. The assessment is conducted by modeling three dimensional steel special moment resisting frame with seismic design category-D. Equivalent lateral force is applied to obtain early identification and response spectrum analysis is used in the next procedure to fulfill additional requirements. Based on SNI 1726:2019, the building has been categorized as horizontal irregularities where torsional irregularities and re-entrant corner irregularities mostly happened. It indicates that the other additional requirements need to be reconsidered such as increasing the design force about 25%, the amplified accidental torsions, P-∆ effect. In the other hand, vertical irregularities do not act toward this building. However, there are some inadequate values of inter-story drifts in X-direction toward drift limit. Then, it is concluded that this asymmetric-plan multi-story building needs to be designed in lateral resistance if this will be planned in future and act the good seismic performance.

1. Introduction
Earthquake is the devastated phenomenon when the massive force attacks to some constructions and may cause the financial loss and casualties. Specifically in Padang city when 2009’s earthquake caused the major damage in constructions include buildings, bridges, roads, etc. Throughout the time, the developments of seismic system in buildings to prevent future earthquake effects have been successfully discovered and applied specifically in steel buildings. Generally, the important aspects to adequate the seismic performances in buildings are stiffness, ductility, lateral strength, and symmetric plan. They are taking the role to determine the behavior of structure response during earthquake motion. However, there are some issues where the symmetric plan is not always the choice for fulfilling the demand of architectural and esthetical due to the limitation of land.
Universitas Dharma Andalas, located in Simpang Haru, Padang city, West Sumatera has the problem in terms of the limitation of land. Figure 1 showed the area where Gedung D will be planned to build but it only has less than 600 m² total areas. It becomes an issue where this land is functionally used as parking area as well. However, turning this land to be fully built new building will decrease 20% of the capacity for parking area which is also main problem in Universitas Dharma Andalas. Then, deciding to build multi-story building with asymmetric plan in this land will be the possible choice to divide that land for parking area and functional building.

There were studies to compare the symmetric and asymmetric plan in terms of their structural responses. The recent studies revealed that asymmetric plan experienced more damage than symmetric plan [1,2]. In asymmetric plan, large displacement and high-stress concentration in partial elements are created due to excessive torsion [3,4,5]. It is because the irregularities in stiffness, mass, and strength that lacking the lateral resistance against earthquake ground motion. Based on SNI 1726:2019 (Indonesian’s Earthquake Code), the irregularities are generally categorized as horizontal and vertical irregularities. The horizontal irregularities are determined as the accidental torsion that cause by asymmetric-plan, diaphragms discontinuities, re-entrant corner, large openings, and non-parallel systems. Vertical irregularities are determined as the sudden change of strength, stiffness, geometry, mass that result irregular distribution forces over height of building [6]. However, in these modern days, the architectural aspect is becoming important to make the building look esthetically. It leads to the possibility of designing asymmetric plan.

Many researchers conducted and developed methods to minimize the torsional effects towards asymmetric plan [7,8]; one of them is the adjacent building [9]. This is claimed as the method to minimize earthquake effects toward asymmetric plan by giving gap between buildings. But, the pounding effect issues come out when two or more different buildings actually have different dynamic properties and the gap distance is inadequate and insufficient for high rise building [10]. In steel structures, using lateral braced is found as the effective way to increase the ductility demand in asymmetric building about 10%-20% [11]. But, it is not still inadequate in terms of floor rotation. The other issues come out when they are only proper for some criteria in horizontal irregularities but not for vertical irregularities [7]. However, asymmetric plan is complicated in terms of efficient and effective design for seismic region especially in steel structures. It needs further comprehension to find out the proper system to get high performance structure since some of codes are still insufficient to accommodate specific characteristic buildings such as long and narrow building and also irregularities in horizontal and vertical [12,5,13]. This paper presents the seismic assessment to identify the characteristic of asymmetric plan in 5-story steel moment resisting frame which is planned to be built.
in Universitas Dharma Andalas, Padang city, West Sumatera. The scope of this paper dominantly assesses the horizontal and vertical irregularities. It could be a basic principle to recognize the probability of future development method to obtain proper seismic design for asymmetric plan buildings.

2. Methodology

2.1 Description of the model

Steel special moment resisting frame (SMRF) is modeled three dimensional by using ETABS 2016 to acquire the seismic responses of asymmetric-plan building. Figure 2 visualizes the building that has five stories with total height 18 m above the ground. Typical story height is 3.5 m except the ground floor has 4 m height and total area of each story is 360 m². This building plan area has been considered for accommodating sufficient numbers of motorcycle in remaining 240 m² parking area. For each element of structures include beams, columns, and deck thickness, they used steel IWF type and the section is determined through preliminary design, details are shown in Table 1. The dead load includes the self-weight of the building and additional load acting on the floor taken as 1.5 kN/m². A live load of 2.5 kN/m² is considered on the typical floor and 1.0 kN/m² at the roof. The total seismic weight of the building is taken as 100% of dead load and 25% of the live load. The building is located in Padang city, West Sumatera with the assumption of site class D; risk category IV; importance factor is equal to 1.5. Thus, \( MCE_R \) parameter response of spectral acceleration in short period \( (S_s) \) is 1,390(\( g \)) and \( MCE_R \) parameter response of spectral acceleration in one second period \( (S_1) \) is 0.60(\( g \)). According to SNI 1726:2019, the steel special moment resisting frame (SRMF) has these designed coefficients \( (R=8, \ C_d=5.5) \). They all used to determine seismic force that act to building.

![Figure 2](image.png)

**Figure 2.** (a) Floor Plan (b) 3D Building Visualization

| Table 1. Details of Structure |
|-----------------------------|
| **Type of Structure**       | Steel Moment Resisting Frame |
| **Number of Story**         | 5-story                      |
| **Material Specification**  | BJ 37                        |
| **Yield Strength (fy)**     | 240 MPa                      |
| **Concrete Strength (fc’)** | 25 MPa                       |
| **Beams**                   | WF 350.175.7.11             |
| **Columns**                 | WF 500.300.13.21            |

| **Type of Structure**       | Steel Moment Resisting Frame |


2.2 **Seismic analysis**

The crucial point to determine seismic analysis and requirements is seismic design category. Based on the constructed response spectrum Figure 3, the values of designed parameter response of spectral acceleration in short period ($S_{D2}$) and designed parameter response of spectral acceleration in one second period ($S_{D1}$) are respectively 0.68 (g) and 0.92 (g). Thus, seismic design category is D.

![Figure 3](image-url)

**Figure 3.** Response Spectrum Design for Padang City, West Sumatera with Site Class-SD

In this research, two types of linear elastic analysis are conducted to obtain seismic responses of asymmetric-plan building; both are equivalent lateral force (ELF) and modal response spectrum analysis (MRSA). Equivalent lateral force is the static analysis that based on the seismic base shear which vertically distributed along the height of structure. This method purposes to early identify the structural behavior in terms of mode shapes and seismic weight of structure. However, there is possibility when asymmetric-plan building is not satisfied the requirements due to the irregularities either in horizontal or vertical. Furthermore, using equivalent lateral force possibly leads to inaccurate results in terms of predict the whole structure responses. Then, modal response spectrum analysis (MRSA), either response spectrum or time history analysis, will be conducted if there are the additional requirements toward irregularities. Basically, In MRSA the structure is idealized as a series of single-degree-of-freedom (SDOF) systems, each having its own mode shape and vibration period. MRSA is permitted for structures in any seismic design category (SDC) and many types of irregularities. In this study, response spectrum analysis will be applied towards building to acquire story displacement due to ground motion.

3. **Result and discussion**

3.1 **Fundamental time period**

Fundamental Time period is the seismic demand that must be early done for structures to identify the structure’s characteristic in terms of deformation. SNI 1726:2019 clauses 7.8.2 proclaims that time period ($T_a$) should be determined by type and height of structure Equation (1). The designed time period ($T$) is compared by ETABS output ($T_c$) for obtaining the modified time period ($T^*$). This value is taken to determine the base shear coefficient of building.

\[ T_a = C_r \cdot h_n^{x} \]  

(Eq.1)

In Table 2, the empirical time period ($T$) in first and second mode has lower result than computed time period ($T_c$). Then, the modified time period ($T^*$) that considered as the main parameter for
calculating base shear is the empirical time period (T). The vibration mode shape is needed to determine the completely response of model. In this study, for this building, the first mode shape is x direct translation and the second mode shape is rotational. According to these results, the building must be assessed toward irregularities and drift limit.

**Table 2. Fundamental Time Period of Building**

| Mode     | T_a (s) | C_u | T = C_uT_a (s) | T_c (s) | T* (s) | Mode Shapes       |
|----------|---------|-----|----------------|---------|--------|------------------|
| 1st Mode | 0.731   | 1.4 | 1.023          | 2.464   | 1.023  | X-Translation    |
| 2nd Mode | 0.731   | 1.4 | 1.023          | 1.681   | 1.023  | Rotational       |

3.2 **Assessment of horizontal irregularities**

For identifying the horizontal irregularities in this building, the story displacements of joint-17 and joint 1 Figure 4 are taken as the view’s point for X-direction. Joint-17 and joint-7 are also taken as the view’s point for Y-direction. The displacement is obtained because of ground motion in x-direction.

![Figure 4. View’s Point of Horizontal Irregularities](image)

In Table 3, the maximum story displacements for ground motion in X-direction (Δ_max) are more than 1.2 times from the average displacement (Δ_avg) and do not exceed 1.4 times. Then, this building is categorized having torsional irregularities (type 1-a). In the other hand, the maximum story displacements for ground motion in Y-direction (Δ_max) are not more than 1.2 times from the average displacement (Δ_avg) and do not exceed 1.4 times. Then, this building is not categorized having torsional irregularities (type 1-a). The additional requirement is needed to fulfill structural stability for seismic design category-D. Based on SNI 1726:2019, the design force for each structural element must be increased about 25%. Besides that, the accidental torsion and P-Δ effects are calculated and considered in the analysis. The amplification factor of torsion (Ax) has been already calculated in Table 3. This value must be considered by multiply them with moment torsion for each story. Furthermore, the inter-story drifts for steel special moment resisting frame with risk category-IV do not exceed the Equation (2).

\[
\Delta_a = 0.015 \cdot h_{sx} \quad \text{(Eq.2)}
\]
Due to torsional irregularities, this building analysis must be re-conducted through the allowable analysis either response spectrum or time history analysis because the equivalent linear static analysis is not allowed to use in building design. This building is also categorized as reentrant corner irregularities where both plan projections of the structure beyond a reentrant corner are greater than 15% of the plan dimension of the structure in the given direction. In Figure 3, building length in A-direction is 24 m, compared to its projection which is B-direction. The length of B is greater than 15% of length in A-direction. It is also greater than 15% of width in C direction when it is compared along width in D-direction. So, there are additional requirements in terms of seismic demand according to SNI 1726:2019.

| Story | Load Case | Joint-17 (mm) | Joint-1 (mm) | Δ17 (mm) | Δ1 (mm) | Δmax (mm) | Δavg (mm) | Δmax/Δavg | Ax |
|-------|-----------|---------------|--------------|----------|----------|-----------|-----------|-----------|----|
| Story-5 | EX        | 55.66         | 35.50        | 7.36     | 4.7      | 7.35      | 6.03      | 1.22      | 1.034 |
| Story-4 | EX        | 48.3          | 30.8         | 7.03     | 4.5      | 7.03      | 5.77      | 1.22      | 1.033 |
| Story-3 | EX        | 41.27         | 26.3         | 9.13     | 6.0      | 9.13      | 7.57      | 1.21      | 1.012 |
| Story-2 | EX        | 32.13         | 20.3         | 12.5     | 7.7      | 12.5      | 10.1      | 1.24      | 1.064 |
| Story-1 | EX        | 19.63         | 12.6         | 19.63    | 12.6     | 19.63     | 16.12     | 1.22      | 1.031 |

\[ \Delta_{\text{max}}/\Delta_{\text{avg}} > 1.2 \quad \Delta_{\text{max}}/\Delta_{\text{avg}} > 1.4 \]

Torsional Irregularities
Not Include
Not Include
Not Include
Not Include
Not Include
Not Include

| Story | Load Case | Joint-17 (mm) | Joint-7 (mm) | Δ17 (mm) | Δ7 (mm) | Δmax (mm) | Δavg (mm) | Δmax/Δavg | Ax |
|-------|-----------|---------------|-------------|----------|--------|-----------|-----------|-----------|----|
| Story-5 | EY        | 40.35         | 33.00       | 4.13     | 3.2    | 4.12      | 3.66      | 1.13      | 0.881 |
| Story-4 | EY        | 36.22         | 29.8        | 5.28     | 5.14   | 5.28      | 5.21      | 1.01      | 0.71  |
| Story-3 | EY        | 30.95         | 24.66       | 6.85     | 6.62   | 6.85      | 6.24      | 1.10      | 0.838 |
| Story-2 | EY        | 24.10         | 19.03       | 9.375    | 9.21   | 9.375     | 8.29      | 1.13      | 0.887 |
| Story-1 | EY        | 14.73         | 11.81       | 14.73    | 11.81  | 14.73     | 13.27     | 1.11      | 0.855 |

\[ \Delta_{\text{max}}/\Delta_{\text{avg}} > 1.2 \quad \Delta_{\text{max}}/\Delta_{\text{avg}} > 1.4 \]

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3.3 Assessment of vertical irregularities
Vertical irregularities are commonly considered if there is irregularity distribution of mass or stiffness on building that may lead to the possibility of soft-story due to the height variations or inequality of distributed mass in each story. The calculation need story stiffness parameter to acquire specification for vertical irregularity. Table 5 and Table 6 show the two requirement categories based on SNI 1726:2019 where each story stiffness in X and Y direction must be checked to 70% of story stiffness above and 80% of average 3 story above.

**Table 5. Drift Limit Based on SNI 1726:2019**

| Story | Story Stiffness (kN/mm) | Story Stiffness >70% story stiffness above | Story Stiffness > 80% from average of 3 story above | Vertical Irregularity Check |
|-------|-------------------------|-------------------------------------------|---------------------------------------------------|-----------------------------|
| Story-5 | 15.300 | Satisfied                          |                                                    | Regular                      |
| Story-4 | 23.882 | Satisfied                          |                                                    | Regular                      |
| Story-3 | 33.555 | Satisfied                          |                                                    | Regular                      |
| Story-2 | 47.488 | Satisfied                          | Satisfied                                         | Regular                      |
| Story-1 | 80.860 | Satisfied                          | Satisfied                                         | Regular                      |

**Table 6. Drift Limit Based on SNI 1726:2019**

| Story | Story Stiffness (kN/mm) | Story Stiffness >70% story stiffness above | Story Stiffness > 80% from average of 3-story above | Vertical Irregularity Check |
|-------|-------------------------|-------------------------------------------|---------------------------------------------------|-----------------------------|
| Story-5 | 20.288 | Satisfied                          |                                                    | Regular                      |
| Story-4 | 31.402 | Satisfied                          |                                                    | Regular                      |
| Story-3 | 43.889 | Satisfied                          |                                                    | Regular                      |
| Story-2 | 61.117 | Satisfied                          | Satisfied                                         | Regular                      |
| Story-1 | 96.668 | Satisfied                          | Satisfied                                         | Regular                      |

The results show either X or Y direction, the story stiffness satisfied the requirements to not be included as vertical irregularities. Story stiffness in story-1 until story-4 has more than 70% story stiffness above. Story stiffness both Story-1 and story-2 also has more than 80% from average of 3-story above. So, there is no additional requirement to assess vertical irregularities in this building.

### 3.4 Drift Limit

Torsional irregularities have caused re-analysis of this building by changing equivalent lateral force into response spectrum analysis or time history analysis. Thus, response spectrum analysis is conducted in ETABS to evaluate another additional requirement, the inter-story drift limit. Figure 5 shows the story displacement between X-direction and Y-direction. These values will be evaluated in Table 7 and Table 8 to assess drift limit based on SNI 1726:2019.

Table 7 and Table 8 show the results of inter-story drift ($\Delta$) and drift limit ($\Delta_0$) both X and Y direction that act along the building’s height. The amplified story displacement ($\delta_0$) is obtained by including the deflection factor ($C_d$) and importance factor ($I_e$). Then, inter-story drift is obtained by subtract the displacement ($\delta_i$) between two close stories. The drift limit ($\Delta_0$) must be divided to redundancy factor ($\rho$) which is determined as 1.3 for structure in seismic design category-D and having irregularities. The results show that the inter-story drift in X-direction for story-1 and story-2 exceeded drift limit while the other inter-story drifts were slightly less than drift limit. Compared to drift limit, the inter-story drift in story-1 and story-2 have exceeded more than 98% and 28% respectively. In other hand, inter-story drift in Y-direction for all stories did not generally exceed drift limit. They also simply visualize in Figure 6.
Figure 5. (a) X-Direction Story Displacement (b) Y-Direction Story Displacement

Table 7. Drift Limit of X-Direction Based on SNI 1726:2019

| Story | Elevation (m) | $\delta_{xe}$ (mm) | $\delta_x$ (mm) | $\Delta_x$ (mm) | $\Delta_{ax}/\rho$ (mm) | Status |
|-------|---------------|---------------------|-----------------|------------------|-------------------------|--------|
| Story-5 | 3.5           | 65.633              | 240.655         | 23.222           | 40.384                  | OK     |
| Story-4 | 3.5           | 59.3                | 217.433         | 30.311           | 40.384                  | OK     |
| Story-3 | 3.5           | 51.033              | 187.122         | 40.211           | 40.384                  | OK     |
| Story-2 | 3.5           | 40.066              | 146.911         | 56.1             | 40.384                  | OK     |
| Story-1 | 4             | 24.766              | 90.811          | 90.811           | 46.153                  | NOT OK |

Table 8. Drift Limit of Y-Direction Based on SNI 1726:2019

| Story | Elevation (m) | $\delta_{ye}$ (mm) | $\delta_y$ (mm) | $\Delta_y$ (mm) | $\Delta_{ay}/\rho$ (mm) | Status |
|-------|---------------|---------------------|-----------------|------------------|-------------------------|--------|
| Story-5 | 3.5           | 27.98               | 102.593         | 9.24             | 40.384                  | OK     |
| Story-4 | 3.5           | 25.46               | 93.353          | 12.833           | 40.384                  | OK     |
| Story-3 | 3.5           | 21.96               | 80.52           | 16.72            | 40.384                  | OK     |
| Story-2 | 3.5           | 17.4                | 63.8            | 22.513           | 40.384                  | OK     |
| Story-1 | 4             | 11.26               | 41.286          | 41.286           | 46.153                  | OK     |

Figure 6. Comparison between Inter-story drift and Drift Limit (a) X-Direction (b) Y-Direction
There is seismic demand that could not be satisfied in X-direction in terms of drift limit. Then, increasing lateral resistance for this building is needed to consider decreasing the exceeded lateral displacements. Furthermore, there are many options in terms of increasing lateral resistance in steel moment resisting frame if asymmetric-plan needs to apply in narrow land. Besides that, changing orientation of composite beams partially is also needed to increase the lateral resistance of asymmetric-plan building in X-direction.

4. Conclusions
This research aimed to assess the irregularities toward multi-story building with asymmetric plan (Gedung-D) due to limitation of land in Universitas Dharma Andalas. Based on the seismic assessment results, there are conclusions can be listed as follows if this plan would be applied:

1. Based on SNI 1726:2019, most of irregularities in asymmetric-plan building (Gedung-D Universitas Dharma Andalas) is the horizontal irregularities where torsional irregularities (type 1-a) and re-entrant corner irregularities (type-2) act toward this building. Then, the allowable analysis procedure is between response spectrum analysis and time history analysis. Other additional requirements are needed to ensure the stability of this structure.
2. The vertical irregularities do not act toward this asymmetric-plan building. Then, soft story issues may not happen in future.
3. Based on response spectrum analysis, there are not satisfied inter-story drifts of story-1 and story-2 in X-direction because exceeded the drift limit. Then, the building needs to be designed further in terms of lateral resistance in steel special moment resisting frame.

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