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The Irregular Response of Flat Plate Structures to Horizontal Deformation for Engineering Decisions

I Gede Untung Wirawan[1], I Nengah Sinarta[1,2*], IGN Putrawan[1]
[1]Professional Engineer Program, Faculty of Engineering and Planning, Warmadewa University
[2]Master Program of Infrastructure and Environmental Engineering, Warmadewa University

ABSTRACT: This study examines the structural response of a seven-story reinforced concrete building with a dual system, focusing on shear forces, stiffness, and inter-story variations. Designed in accordance with SNI 1726-2019 for Jakarta, the study considers dead loads, live loads, wind loads, rain loads, and earthquake loads. Analysis on the second floor (6.2 m above the foundation) indicates that the inter-story deflections meet the permissible limits, with a maximum deviation of 64.615 kN at the roof and 49.23 kN from floors 2 to 6. Static shear forces reached 41,826.62 kN (X) and 4,182.62 kN (Y), while dynamic shear forces reached 4,697.28 kN (X) and 5,057.97 kN (Y), meeting the static force requirement of 100%. Overall, the shear forces, stiffness, and inter-story deviations of Building B demonstrate an effective structural response to earthquake activity. Engineers are expected to master the behavior of irregularities in structural elements due to earthquake loads so that they can make informed decisions in construction planning and its implementation in the field.

KEYWORDS: Flat slab, earthquakes, deformation, engineer

I. INTRODUCTION

The building structure can be defined as a set of elements or components that serve as the fundamental framework enabling the construction to stand, designed in such a way as to withstand the loads acting upon it (Wiranata & Sinarta, 2023). Even if there are two different materials, they must still meet stability requirements (Putra et al., 2020). The structural design process generally consists of two main stages: determining internal forces using appropriate structural analysis methods, and determining the dimensions or sizes of each structural element economically (Teruna & Prawira, 2016), while considering safety factors, stability, serviceability, and the intended function of the structure (Setiawan, 2016). With the advancement of science and technology in the construction field, various structural systems have been developed to optimize their benefits (Primakov & Leo, 2019).

In the design of multi-story buildings, there is a tendency to maximize efficiency through cost-saving strategies, provided that these do not compromise the structural integrity of the building. One innovation often applied is the use of a flat slab system. A flat slab is a reinforced concrete slab directly supported by concrete columns without the use of beam (Hs, 2002). Flat slabs possess adequate shear strength, particularly when enhanced with drop panels, column capitals, or both. A drop panel refers to a thickened portion of the slab around the column support area, functioning to reduce punching shear stress transferred from the column to the slab (Cahyana et al., 2022). A column capital, on the other hand, is a widened section at the top of the column that helps increase the slab's capacity to resist shear forces (I Gusti Ngurah Agung Eka Arya et al., 2023). The use of flat slabs in building structures offers several advantages (Hs, 2002), including Reduction in overall building height, Shorter construction time, Easier installation of mechanical and electrical services.

II. LITERATURE REVIEW

The building structural system using flat slabs has been studied by several researchers from various perspectives. This review aims to understand the correlation between previous research findings and the current thesis. One relevant study is the analysis of flat slabs with square column drop panels under varying live load conditions.

(Varghese, 2020) analysed live load planning on building structures using the ETABS application. They found that when live loads are unevenly distributed on the slab and produce greater moments than uniformly distributed live loads, the structural design should be based on the uneven live load to prevent structural failure (I Wayan Maesa Andreasnata et al., 2022).

The analysis indicated that the moment due to uneven live loads is higher than that from uniform live loads. Therefore, the structural design was planned to account for uneven live loads on the slab, ensuring greater safety in the event of uneven live loads (Pungus, 2020).

III. RESEARCH METHOD

This study focuses solely on analysing and designing the structure of Building B at Rusun Jalan Tongkol using a flat slab system with drop panels. The design follows the Indonesian National Standard (SNI)((BSN), 2019; Badan Standardisasi Nasional, 2020), applying the concept of load and resistance factor design. The stress induced in the structure must be less than the allowable stress, with the requirement that the design strength exceeds the required strength (Teruna & Prawira, 2016).

In this analysis, various software tools were utilized: AutoCAD for architectural data preparation, ETABS version 20 for structural modeling and internal force calculation, and Microsoft Excel to assist in analysing the output results from the internal force data.

Table 1. Data collection

No	Element under review	Indicator
1	Plans, details, and sections serve as references for structural design preparation.	Architechtural Drawing
2	To determine and calculate the foundation, the cone resistance value (qc) and the total skin friction value must be identified.	Soil Data

IV. RESEARCH METHOD

There are two key calculations required in this section: the seismic base shear force and the inter-story drift.

4.1 Seismic Base Shear Force

The seismic base shear force, caused by dynamic earthquake loading (response spectrum analysis), must be examined and compared with the seismic base shear resulting from static earthquake loading. This comparison ensures that the dynamic response satisfies the design earthquake force requirements . The steps of the analysis are as follows:

1. Determination of the Earthquake Resistance System

The Ditreskrimsus Polda Bali building is designed using a special moment-resisting reinforced concrete frame system. Based on Table 12 of SNI 1726:2019, the following values are obtained: Response modification coefficient (R): 8 ; Deflection amplification factor (Cd):5.5; System overstrength factor (Ω_0): 3

2. Effective Seismic Weight

The effective seismic weight of the building is obtained from ETABS version 20, 2024 as follows:

Table 2. Weight of floor

Floor	Weight (kN)
Roof Floor	3861,15
7th Floor	5957,89
6th Floor	5760.19
5th Floor	5760.19
4th Floor	5760.19
3rd Floor	5760.19
2nd Floor	5957,89
1st Floor	3008,57
Pedestal	395,4
Total	**41826,2**

3. Determination of the Approximate Fundamental Period

Based on the calculations presented in subsection 4.5.1, the fundamental period of the structure is obtained as follows:

Table 3. Fundamental period

X Direction	Y Direction
T_a = 0,826 second	T_a = 0,826 second
T_{cx} = 0,755 second	T_{cy} = 0,817 second
T_{max} = 1,156 second	T_{max} = 1,156 second
T_{pakai} = 0,826 second	T_{pakai} = 0,826 second

4. Determination of the Seismic Response Coefficient

The following values are known:

$S_{DS} = 0{,}8$

$S_{D1} = 0{,}800$

$R = 8$

$I_e = 1{,}0$

$T = 0{,}826$ second

The seismic response coefficient Cs is determined using the following formula:

$$C_S = \frac{S_{DS}}{\left(\frac{R}{Ie}\right)} = \frac{0{,}80}{\left(\frac{8}{1}\right)} = 0{,}100$$

The calculated value of Cs must not exceed the following limit:

For $T \leq T_L$:

- **X Direction:**

$$C_{S,max} = \frac{S_{D1}}{T\left(\frac{R}{Ie}\right)} = \frac{0{,}80}{0{,}826\left(\frac{8}{1}\right)} = 0{,}121$$

C_S should be no less than:

$C_{S,min} = 0{,}035 S_{DS}\, I_e \geq 0{,}01$

$C_{S,min} = 0{,}035{,}0{,}80{,}1{,}0 \geq 0{,}01$

$C_{S,min} = 0{,}028 \geq 0{,}01 C_{S,use} = 0{,}100$

- **Y Direction:**

$$C_{S,max} = \frac{S_{D1}}{T\left(\frac{R}{Ie}\right)} = \frac{0{,}80}{0{,}826\left(\frac{8}{1}\right)} = 0{,}121$$

C_S should be no less than :

$C_{S,min} = 0{,}035 S_{DS}\, I_e \geq 0{,}01$

$C_{S,min} = 0{,}035{,}0{,}80{,}1{,}0 \geq 0{,}01$

$C_{S,min} = 0{,}028 \geq 0{,}01$

$C_{S,pakai} = 0{,}100$

To enhance clarity and facilitate understanding, the data are presented in the following table :

Table 4. Parameter calculate

X Direction	Y Direction
Cs,min = 0,035	Cs,min = 0,035
Cs = 0,100	Cs = 0,100
Cs,maks = 0,121	Cs,maks = 0,121
Cspakai = 0,100	Cspakai = 0,100

5. Base Shear Force

The base shear force due to static earthquake loading is calculated as follows :

$$V = C_S . W$$

X Direction

$$V = 0{,}100\ .\ 41826{,}2$$

$$V_x = 4182{,}62 kN$$

Y Direction

$$V = 0{,}100 . 41826{,}2$$

$$V_y = 4182{,}62\ kN$$

The basic shear force due to dynamic earthquakes was obtained from ETABS v18 as follows

$$V_{tx} = 4697{,}28\ \ kN$$

$$V_{ty} = 5057{,}97 kN$$

According to the provisions of SNI 1726:2019 (Badan Standar Nasional Indonesia, 2019), the dynamic base shear force must be at least 100% of the static base shear force. Therefore, since the dynamic shear force has reached 100% of the static shear force, the requirement is considered fulfilled.

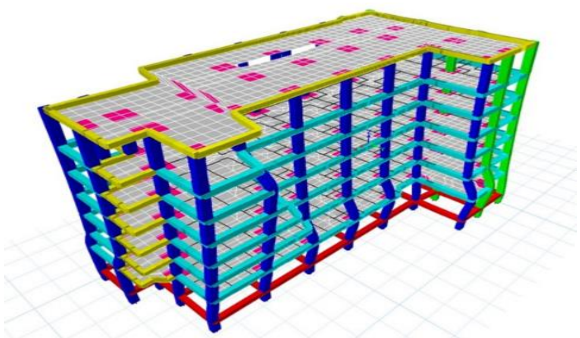

Figure 1. Dynamic deformations

4.2 Inter-Story Drift

1. Inter-story Drift Control in the X-Direction

As an example, the inter-story drift calculation for the 7th floor is presented as follows:

a. Horizontal Deformation due to Design Earthquake Load

The maximum horizontal deformation resulting from the design earthquake load in the X-direction is obtained from ETABS v.20, 2024, as follows:

Table 5. Deformation X-direction

Level	δx (mm)
Roof Floor	22.866
7th Floor	21,014
6th Floor	19,184
5th Floor	16,722
4th Floor	13.650
3rd Floor	10,076
2nd Floor	6,163
1st Floor	0,931
0	0,00

b. Determination of Inter-Story Drift, (Δ_x)

$$\Delta_x = \frac{(\delta_x - \delta_{(x-1)})C_d}{I_e}$$

I_e =based on Table 4, SNI 1726:2019

C_d = based on Table 12, SNI 1726:2019

$$\Delta_x = \frac{(\delta_x - \delta_{(x-1)})C_d}{I_e}$$

$$\Delta_x = \frac{(22{,}866 - 21{,}014)5{,}5}{1{,}0}$$

$$\Delta_x = 10{,}186\ mm$$

c. Determination of Allowable Drift, (Δ_a)

Based on section 7.12.1 and Table 20, the deviation between the SNI 1726: 2019 permit floor for a 7-story building with risk category II and section 7.3.4.2 redundancy factor for design category D is taken as 1.3, then:

$$\Delta_a = \frac{0{,}02 . h_{sx}}{1{,}3}$$

$$\Delta_a = \frac{0{,}02 . 4200}{1{,}3}$$

$$\Delta_a = 64{,}615\ mm$$

d. Inter-Story Drift Check

$$\Delta_x = 10{,}186\ mm$$

$$\Delta_a = 64{,}615\ mm$$

$$\Delta_x < \Delta_a = 10{,}186\ mm < 64{,}615\ mm\ (OK)$$

The calculations for the deviation between floors are presented in the following table 6:

Table 6. deviation X-direction of the level

No	Story	hsx	δx	Δx	Δa	Δx < Δa
		mm	mm	mm	mm	
8	Roof floor	4200	22,866	10,186	64,615	OK
7	Floor 7	3200	21,014	10,065	49,231	OK
6	Floor 6	3200	19,184	13,541	49,231	OK
5	Floor 5	3200	16,722	16,896	49,231	OK
4	Floor 4	3200	13,65	19,657	49,231	OK
3	Floor 3	3200	10,076	21,522	49,231	OK
2	Floor 2	3200	6,163	28,776	49,231	OK
1	Floor 1	4200	0,931	5,121	64,615	OK
0	0	0	0,00	0,000	0	OK

2. Inter-story Drift Control in the Y-Direction

As an example, the inter-story drift calculation for the 7th floor is presented as follows:

a. Horizontal Deformation due to Design Earthquake Load

The maximum horizontal deformation resulting from the design earthquake load in the Y-direction is obtained from ETABS v.20, 2024, as follows:

Table 7. Deformation Y-direction.

Level	δ_Y (mm)
Roof Floor	35,196
7th Floor	32,278
6th Floor	29,366
5th Floor	25,459
4th Floor	20,584
3rd Floor	14,94
2nd Floor	8,97
1st Floor	1,333
0	0,00

b. Determination of Inter-Story Drift, (Δ_x)

$$\Delta_y = \frac{(\delta_y - \delta_{(x-1)})C_d}{I_e}$$

where:

I_e = 1.0 (based on Table 4, SNI 1726:2019)

C_d = 5.5 (based on Table 12, SNI 1726:2019)

$$\Delta_y = \frac{(\delta_y - \delta_{(x-1)}).C_d}{I_e}$$

$$\Delta_y = \frac{(35{,}196 - 32{,}278).5{,}5}{1{,}0}$$

$$\Delta_y = 16{,}049\ mm$$

c. Determination of Allowable Drift, (Δ_a)

Based on section 7.12.1 and Table 20, the deviation between the SNI 1726: 2019 floor permit for a 4-story building with risk category II and section 7.3.4.2, the redundancy factor for design category D is taken as 1.3, therefore:

$$\Delta_a = \frac{0{,}02.h_{sx}}{1{,}3}$$

$$\Delta_a = \frac{0{,}02.4200}{1{,}3}$$

$$\Delta_a = 64{,}615\ mm$$

d. Inter-Story Drift Check

$$\Delta_y = 16{,}049\ mm$$

$$\Delta_a = 64{,}615\ mm$$

$$\Delta_y < \Delta_a = 16{,}049\ mm < 64{,}615\ mm\ (OK)$$

The calculations for the deviation between floors are presented in the following table:

Table 8. Deviation Y-direction of the level

No	Story	hsx	δy	Δy	Δa	Δy < Δa
		mm	mm	mm	mm	
8	Roof floor	4200	35,196	16,049	64,615	OK
7	Floor 7	3200	32,278	16,016	49,231	OK
6	Floor 6	3200	29,366	21,489	49,231	OK
5	Floor 5	3200	25,459	26,813	49,231	OK
4	Floor 4	3200	20,584	31,042	49,231	OK
3	Floor 3	3200	14,94	32,835	49,231	OK
2	Floor 2	3200	8,97	42,004	49,231	OK
1	Floor 1	4200	1,333	7,332	64,615	OK
0	0	0	0,00	0,000	0	OK

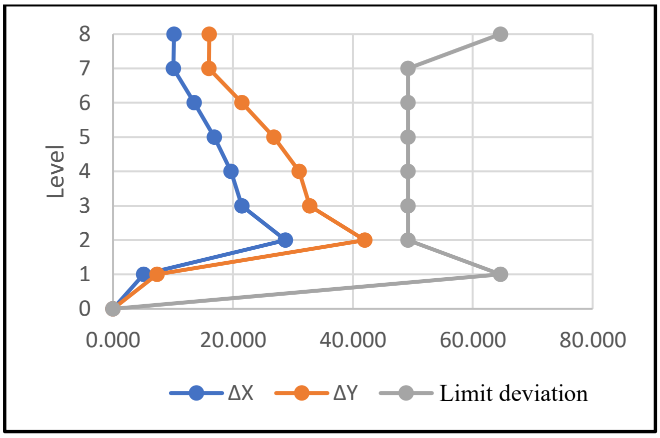

Figure 2. Level diviation

Based on the graph above, the inter-story drift in both the X and Y directions is smaller than the allowable drift. Therefore, the designed structure is considered stable and meets the required criteria.

V. CONCLUSIONS

Based on the results of data analysis and discussion regarding the structural response of the flat slab-drop panel system, the following conclusions can be drawn:

1. The displacement analysis for Tower B in the X-direction shows a maximum displacement occurring on the second floor, with a value of 28.776 mm. In the Y-direction, the maximum displacement also occurs on the second floor, with a value of 42.004 mm. The allowable displacement limit is 64.615 mm. Therefore, the displacement analysis satisfies the specified requirements and is illustrated in Figure 2.
2. The shear force analysis for Tower B under dynamic earthquake loading shows a value of 4,697.28 kN in the X-direction and 5,057.97 kN in the Y-direction.
3. Based on the floor levels from bottom to top, the displacement values are inversely proportional to the shear force values, but directly proportional to the stiffness at each floor level.
4. The overall results of the response spectrum analysis — including displacement, shear force, and stiffness level — indicate that Tower B, which utilizes a flat slab-drop panel system, demonstrates a good structural response to the applied seismic forces.

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