Study of Base Shear and Inter-Story Drift due to Earthquake Forces on a Ten-Story Building Structure in Surakarta

Yudistira Cahaya Assidiq, Ika Bali*

Department of Civil Engineering, President University, Cikarang, Indonesia

Received 2 December 2024; received in revised form 05 April 2025; accepted 07 April 2025

Abstract

Earthquakes are the frequent natural disasters that hit Indonesia as a consequence of the country's geographical location. Surakarta City become a region that frequently suffers the effects of earthquakes. Earthquake disasters threaten high-rise building structures in Surakarta City, where earthquake loads acting on the structure can cause damage and even structural collapse. These historical and geographical reasons become the foundation of this study to analyze high-rise building structures in Surakarta City. In this study, the structural conditions of the analyzed high-rise buildings comply with the equivalent static method's analysis requirements, so that this method can be employed in this research. The equivalent static analysis was conducted through manual calculation and the ETABS program. This study focuses on several structural parameters, including base shear force, and inter-story drift. Based on the analysis that was already conducted, the base shear force was obtained at 14392.365 kN through manual calculation and 14984.490 kN through ETABS program analysis. The inter-story drift value that was already calculated fulfils the maximum threshold requirements, where the inter-story drift values are 17.984 mm – 68.183 mm in the X direction and 9.846 mm – 46.804 mm in the Y direction.

Keywords: earthquake forces, high-rise building, base shear force, inter-story drift

1. Introduction

An earthquake is a seismic wave formed by a sudden release of energy inside the earth that causes movement, vibration, or shock on the earth's surface. Indonesia is a region that is geographically highly vulnerable to earthquakes or seismic disasters. This is due to Indonesia's position at the meeting point of three of the world's large lithospheric plates and on the Pacific Ring of Fire [1-2]. This geographical fact is proven by the high frequency of earthquake disasters in Indonesia. Based on data from the Indonesian Meteorology, Climatology and Geophysics Agency, there are 11,395 earthquakes recorded in 2021 and 10,843 earthquakes in 2022 [3].

The vulnerability of Indonesia's area to earthquakes has caused concerns about structure building construction in Indonesia [4], where the majority of structural systems used are reinforced concrete moment-resisting frame systems [5-6]. This concern has become actual with the large number of the reinforced concrete structures being constructed, especially high-rise building construction in urban areas, due to the increasing demand for providing space for activities, both as a place to work (office and business), for entertainment (shopping centre), and as a place to live (residential, hotel, apartment) [7]. The concern derives from the fact that high-rise buildings have a significant risk of structural failure and collapse when subjected to seismic or earthquake forces. The suitable planning and analysis of structures can reduce the collapsing risk of high-rise buildings under seismic or earthquake forces [8-15]. The planning and analysis in Indonesia must be guided by the Indonesian

* Corresponding author. E-mail address: ika.bali@president.ac.id
Tel.: +62(0)21 89109763

National Standard (SNI) 1726-2019 [16] concerning the procedures for the design of earthquake resistance building and non-building structures. Analysis of high-rise buildings against earthquake forces is split into two categories, namely static analysis (static equivalent analysis and pushover analysis) and dynamic analysis (response spectrum analysis and time history analysis) [17].

The suitable planning and analysis of the building structure against earthquake forces is required to ensure that the building structure is resistant to earthquakes (earthquake-resistant building). An earthquake-resistant buildings are buildings that can withstand and not collapse if an earthquake occurs. Earthquake-resistant buildings do not mean they cannot be damaged at all, but earthquake-resistant buildings can be damaged as long as they still fulfil the applicable requirements [18].

Equivalent static analysis is an analysis structures method against earthquake load using equivalent static nominal earthquake loads that work on the centre of mass of each level. This structural analysis was conducted by modelling the static horizontal load derived under the influence of the first earthquake response [19-20]. The main parameters or factors of the building structure analysed in this study are the base shear force, structural drift, and inter-story drift.

Base shear force is the output of equivalent static analysis in maximum lateral force that works on a structure's base (foundation) due to earthquake vibrations and will be used as the design earthquake force [21]. Story displacement is the output of equivalent static analysis in maximum horizontal displacement values due to static earthquake loads acting at the height of high-rise building structures and will be used as the basic for calculating structural drift at the mass centre of each story [22]. The inter-story drift is the difference value of the maximum structural drift between two adjacency floors of the building or at each building level [21-23].

2. Literature Study

Equivalent static analysis uses equivalent static nominal earthquake loads that act on the mass centre of each story as input in this analysis against earthquake loads. This structural analysis method models horizontal static earthquake loads obtained as a result of the first earthquake variation response. The modelled horizontal loads are equivalent as a substitute for the dynamic load effects that occur during an earthquake. The horizontal loads modelled in this analysis trigger changes in the building structure, in this case damage to structural elements, structural damage, and even structural collapse. The procedures and requirements of this equivalent static analysis are listed in SNI 1726-2019. This code explains that this static analysis is only for regular buildings according to the requirements below:

1. 40 meters or 10 floors as the maximum limit of the elevation of the structure.
2. The rectangular shape structure without protrusions or with protrusions of less than 25% of the size of its structure plan.
3. The structure does not have corner notches or has corner notches with a length of more than 15% of the length of the side of the crack direction.
4. The structural system does not have a stepped face or has a stepped face (the size of the structure in each direction is not less than 75% of the largest size of the structure below).
5. The structural system has measured lateral stiffness, where no floor has a lateral stiffness of less than 70% of the floor above it.
6. The structural system has vertical elements that support continuous lateral loads, without displacement of the center of gravity.
7. The structural system has continuous floors, without or with holes at that level with an area of less than 50% of the floor area.

In this study, the equivalent static analysis is conducted by two types of methods, namely manual calculation (Microsoft Excel) and by using the ETABS program [24]. Output from equivalent static method using the structural analysis program includes base shear force and story displacement (elastic displacement). After obtaining the output of the equivalent static analysis, several structural parameters, such as structural drift and inter-story drift can be calculated and checked by using equations and requirements listed in the Indonesian National Standard (SNI 1726-2019). These structural parameters are checked to determine that the structure can withstand earthquake forces.

The first output of the equivalent static analysis is the base shear force (V), which is a maximum lateral force (structural shift) that acts on the foundation (base) of a building structure due to earthquake vibrations. The maximum lateral force or structural shift will cause story displacement so that there will be a decrease in strength or even structural collapse. In addition to being obtained from the analysis in the ETABS Program, the base shear force (V) can also be calculated and done using the equation below and is used as the design earthquake force in the structural analysis of earthquake forces.

$$V = C_s \times W \tag{1}$$

where C_s is the coefficient of seismic response, W is the effective weight.

The second output of the equivalent static analysis is the story displacement or elastic displacement (d_{xe}), which is maximum horizontal displacement values due to static earthquake loads acting at the height of high-rise building structures. The story displacement (d_{xe}) value is used as the basic for calculating structural drift at the mass centre of each story (d_x). Below is the equation used to determine structural drift or inelastic displacement at the mass centre of each story (mm):

$$d_x = \frac{Cd \times d_{xe}}{I_e} \tag{2}$$

where Cd is the deflection magnification factor that obtained from Table 12 in SNI 1726-2019, d_{xe} is the story displacement at the x-level, and I_e is the earthquake priority factor that obtained from Table 4 in SNI 1726-2019.

The difference between the structural drift at the mass centre of a story and the structural drift at the mass centre of the story above it is calculated to obtain the inter-story drift value (Δ_x). Inter-story drift determination in structures that have vertically misaligned mass centres is done by projecting the mass centre of the ground floor. The inter-story drift (Δ_x) values that occurs in each story of building structure must meets maximum limits which is called the permissible inter-story drift ($\Delta_{a(x)}$). The inter-story drift at the 1st floor (Δ_1) value is calculated from the structural drift of the 1st floor value as in the below equation:

$$\Delta_1 = d_1 < \Delta_{a(1)} \tag{3}$$

Whereas the calculation of inter-story drift at 2nd floor or more, it can be used the equation below:

$$\Delta_x = (d_x - d_{(x-1)}) < \Delta_{a(x)} \tag{4}$$

where d_x is the structural drift that occurs at x-level, and $\Delta_{a(x)}$ is the permissible inter-story drift at x level.

Based on article 7.12.1 of SNI 1726-2019, building structures that suffer inter-story drift due to earthquake forces can be categorized as safe buildings if they meet the permissible inter-story drift requirements. The permissible inter-story drift value is obtained from the equation in Table 1 below.

Table 1 The permissible inter-story drift

Structure	Risk category I or II	Risk category III	Risk category IV
Building structures, except shear wall structures with 4 stories or less with partition walls, interior, ceiling, and exterior wall systems.	$0.025 \times h_{sx}$	$0.020 \times h_{sx}$	$0.015 \times h_{sx}$
Cantilever shear wall structure	$0.010 \times h_{sx}$	$0.010 \times h_{sx}$	$0.010 \times h_{sx}$
Other shear wall structure	$0.007 \times h_{sx}$	$0.007 \times h_{sx}$	$0.007 \times h_{sx}$
Other structures	$0.020 \times h_{sx}$	$0.015 \times h_{sx}$	$0.010 \times h_{sx}$
Notes: h_{sx} = The high level below level-x			

3. Methodology

This study aims to determine the effect of earthquake forces on the value of base shear force and inter-story drift of the structure using the equivalent static analysis method. This study was carried out based on appropriate and proper systematic principles to ensure the study ran smoothly. The systematic basis used in this study will be explained and described in a study methodology. The study methodology will explain how the study was conducted to derive results and conclusions from the study. The study methodology is displayed in Fig. 1 below.

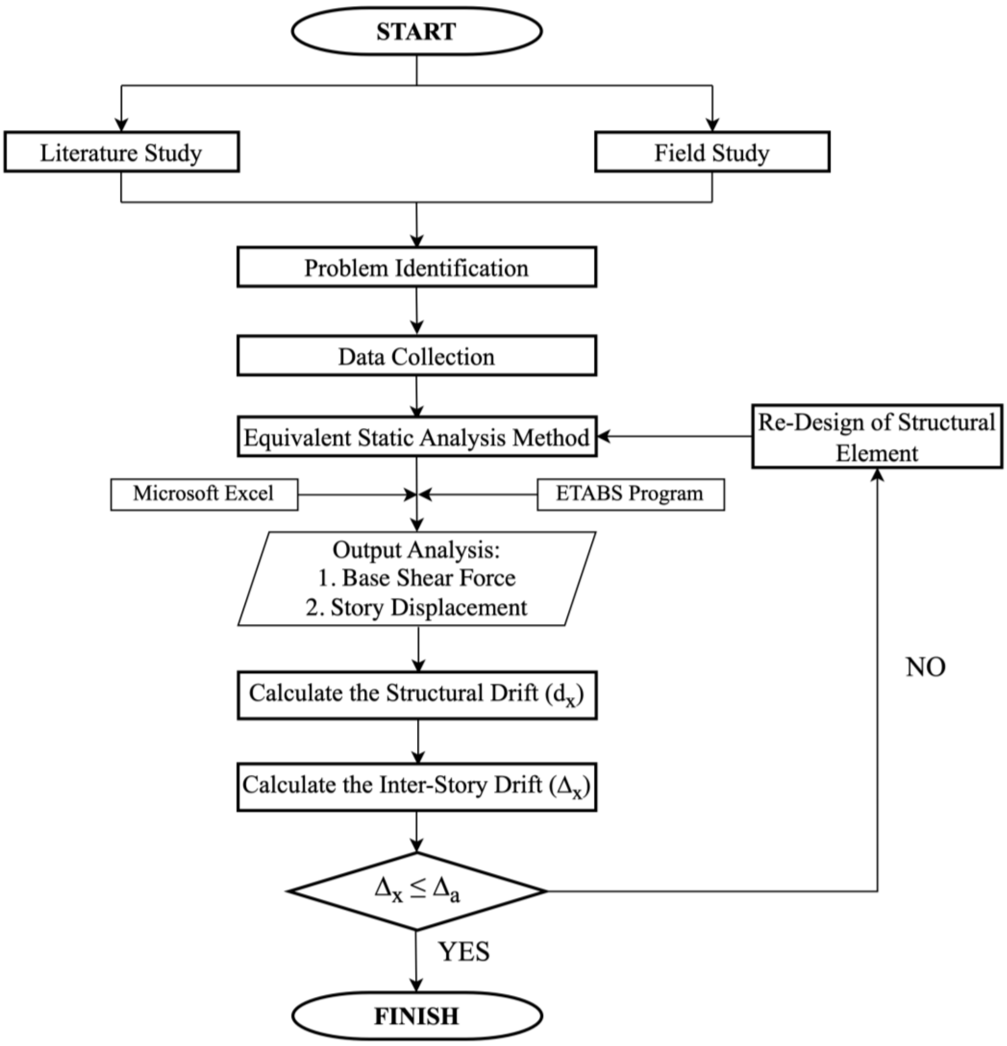

Fig. 1 Study methodology

This study uses an object in the form of an open frame system for reinforced concrete building structure, where the building structural system consists of beams and columns with moment-resistant connections. The building structure is located on Slamet Riyadi Street, Serengan, Surakarta City. The site class of this structure is on medium soil (SD) with regosol soil type. The site of the structure is approximately 38.38 km from the Merapi-Merbabu Fault and 41.38 km from the Opak Fault. The building structure used as the object of this study has the following characteristics:

1. Building structure function : Hotel (risk category II, Ie: 1.0)
2. Number of floors : 10 Levels
3. Elevation
   a. 1^{st} – 9^{th} story height : 3.6 meters
   b. 10^{th} story height : 3.4 meters
   c. Highest elevation : +35.80 meters
   d. Lowest elevation : +0.00 meters
4. Total building area : 6297.60 m^2
5. Structural elements
   a. Beam ($f_c{}' = 30\ MPa$)
      - Beam I (concrete, dimension: 350 x 600 mm)
      - Beam II (concrete, dimension: 250 x 500 mm)
   b. Column ($f_c{}' = 30\ MPa$)
      - Column (concrete, dimension: 700 x 700 mm)
   c. Slab ($f_c{}' = 30\ MPa$)
      - Floor Slab (concrete, thickness: 120 mm)
   d. Reinforcement
      - Longitudinal Reinforcement (steel, $f_y = 400\ MPa$)
      - Transversal Reinforcement (steel, $f_y = 300\ MPa$)

The structural plan drawings required in this study, including site plan drawing, beam detail drawing, and column detail drawing (due to data limitations, the drawings are assumed to be based on field conditions) are shown in Fig. 2 and Fig. 3 below.

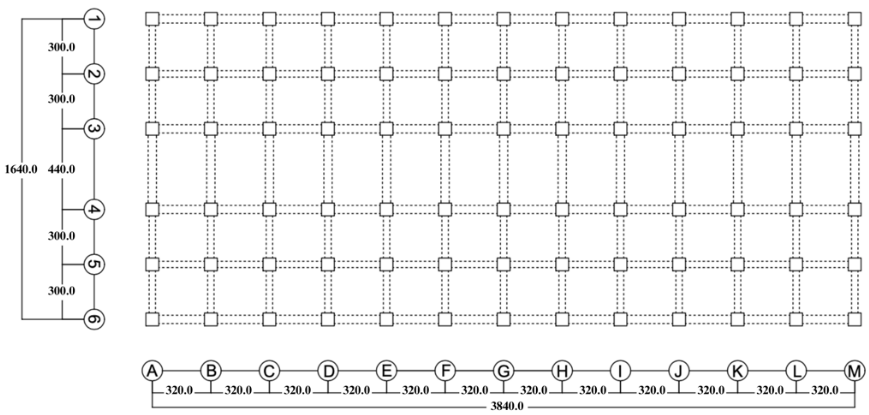

Fig. 2 Site plan

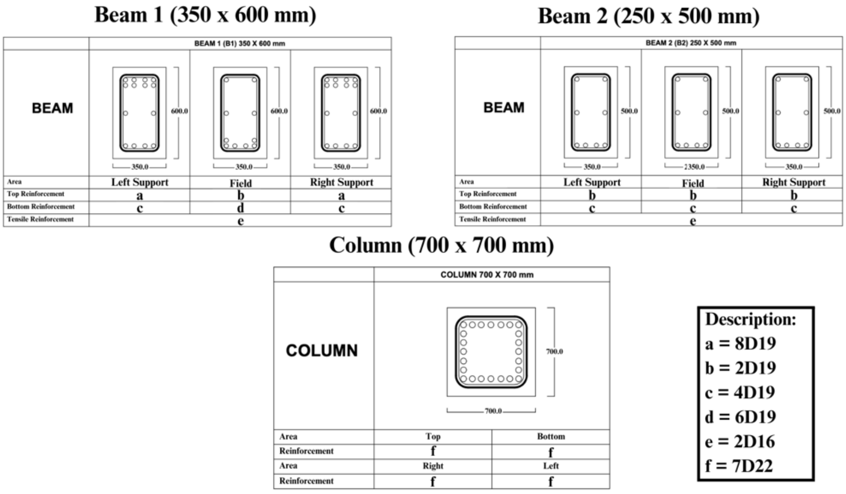

Fig. 3 Beam and column details

4. Results and Discussion

In static equivalent analysis, the structural weight is the essential parameter required. Therefore, the process of calculating the structural weight on each floor is a crucial step in this analysis. The structural weights are obtained from the combination of dead, superimposed dead, and live load (1.2DL+1.2SDL+1.6LL). The calculation of the weight of structure on each floor is displayed in Table 2 below.

Table 2 The weight of structure

Story	Elevation (m)	Weight of structure	
		W_x (kN)	W_y (kN)
Level 10	35.8	17990.31	17990.31
Level 9	32.4	27000.51	27000.51
Level 8	28.8	27512.19	27512.19
Level 7	25.2	27512.19	27512.19
Level 6	21.6	27512.19	27512.19
Level 5	18.0	27512.19	27512.19
Level 4	14.4	27512.19	27512.19
Level 3	10.8	27512.19	27512.19
Level 2	7.2	27512.19	27512.19
Level 1	3.6	27512.19	27512.19
Base	0.0	9210.20	9210.20

In addition to the weight of structure, the static equivalent analysis requires several seismic response spectrum parameters. The seismic response spectrum parameters can be calculated manually with the reference of SNI 1726-2019 or with the Indonesian Spectra Design website [25]. For Surakarta City as the location of the building structure, it has the seismic response spectrum parameter values as displayed in Table 3 below and the seismic response spectrum is shown in Fig. 4 below.

Table 3 Seismic response spectrum parameters

Parameters	Value	Units	Parameters	Value	Units
S_s	0.797	g	S_{DS}	0.630	g
S_1	0.386	g	S_{D1}	0.490	g
F_a	1.181	g	T_0	0.160	s
F_v	1.914	g	T_s	0.780	s
S_{MS}	0.942	g	T_L	20	s
S_{M1}	0.739	g			

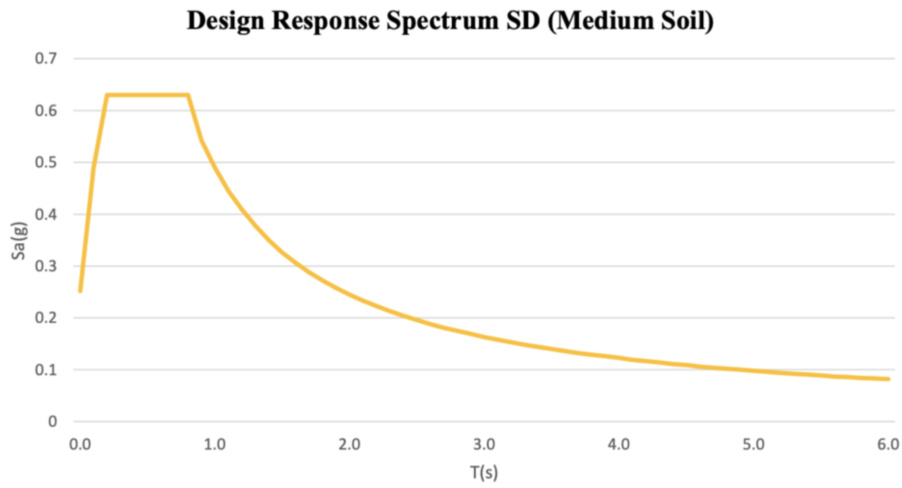

Fig. 4 The design response spectrum (Surakarta city/medium soil)

After obtaining several seismic parameter values of the response spectrum, the approximate fundamental period of the structure (T_a) and the seismic response coefficient (C_s) were calculated. The calculation of the fundamental approach period of the structure uses equation (36) and Table 18 in SNI 1726-2019. Below is the calculation of the approximate fundamental period of the analyzed structural:

$$Ct = 0.0466; x = 0.9; h_n = 35.8\, meter$$

$$T_a = Ct \times (h_n{}^x) = 0.0466 \times (35.8^{0.9}) = 1.166\, s$$

In calculating the seismic response coefficient (C_s), the R value of 8, Cd value of 3.5, and Ωo value of 3 were obtained using Table 12 in SNI 1726-2019 (Specific Moment Resisting Reinforced Concrete Frames). The calculation of the seismic response coefficient (C_s) is carried out using equation (31) in SNI 1726-2019. In addition, the maximum and minimum limits were calculated using equations (32) and (34) in SNI 1726-2019. Below is the calculation of the seismic response coefficient (C_s):

$$C_s = \frac{SDS}{\left(R/_{Ie}\right)} = \frac{0.63}{\left(8/_1\right)} = 0.0788$$

$$C_{s\,max} = \frac{SDS}{T_a\left(R/_{Ie}\right)} = \frac{0.63}{1.166\left(8/_1\right)} = 0.0525; C_{s\,min} = 0.044 \times SDS \times Ie = 0.044 \times 0.63 \times 1 = 0.0277$$

From the above calculation, it can be seen that the C_s value is greater than $C_{s\,max}$ ($C_s > C_{s\,max}$), so the C_s value used is 0.0525 ($C_s = C_{s\,max}$).

Using the calculated parameters, an equivalent static analysis can be conducted to obtain the base shear force and story displacement values. In this study, the base shear force value is obtained from manual calculations using the equation (1) and ETABS program analysis as listed in Table 4 below.

Table 4 Base shear forces value from manual calculation and ETABS analysis

Earthquake load		$V_x\ (kN)$	$V_y\ (kN)$
Manual calculation	Eq X	14392.365	0
	Eq Y	0	14392.365
ETABS analysis	Eq X	14984.490	0
	Eq Y	0	14984.490

From Table 4 above, the difference value between the base shear forces from manual calculation ($V_x = V_y = 14392.365\ kN$) and ETABS analysis ($V_x = V_y = 14984.490\ kN$) is 0.0395 (3.95%).

In addition to obtaining the base shear force value as the first output, the maximum story displacement value in the X direction and Y direction is obtained as the second output in the equivalent static analysis. In this study, the maximum story displacement values in the X and Y directions were obtained from the equivalent static analysis conducted in the ETABS program. The maximum story displacement that occurs on the analyzed structure building is shown in Fig. 5 below. After that, the structural drift value at the mass center of each floor was calculated using the maximum story displacement value and equation (2). The results of the structural drift calculation are shown in Table 5 below.

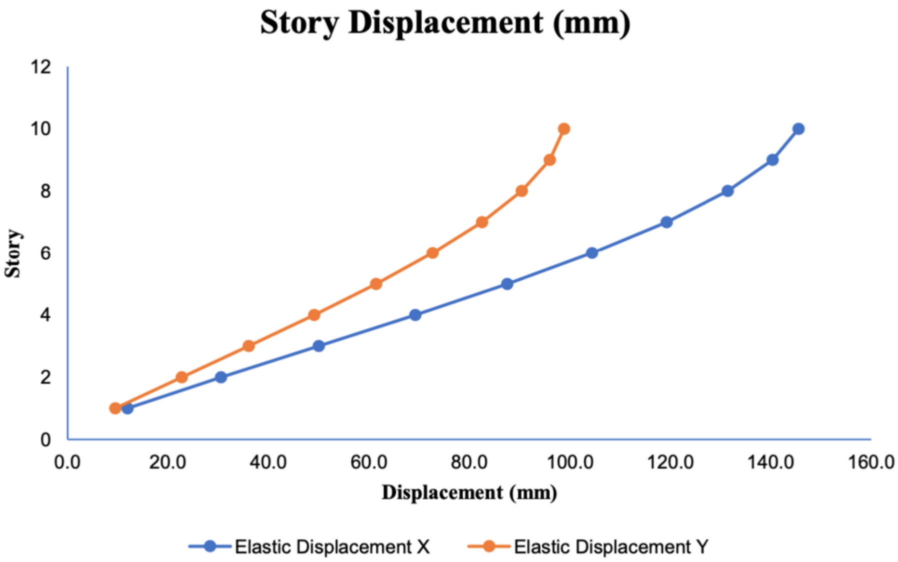

Fig. 5 Story displacement

Table 5 Structural drift

Story	Elastic displacement		Structural drift	
	X-direction (mm)	Y-direction (mm)	X-direction (mm)	Y-direction (mm)
Level 10	145.533	98.801	509.367	345.805
Level 9	140.395	96.988	491.383	335.959
Level 8	131.453	90.389	460.087	316.362
Level 7	119.242	82.464	417.346	288.624
Level 6	104.384	72.661	365.342	254.315
Level 5	87.501	61.405	306.255	214.916
Level 4	69.185	49.088	242.149	171.807
Level 3	49.991	36.071	174.968	126.249
Level 2	30.510	22.698	106.785	79.445
Level 1	11.906	9.500	41.671	33.250

The structural drift or inelastic displacement (d_x) from the results of the equivalent static analysis with the ETABS program is referred to as the basic calculation of the inter-story drift (Δ_x). Furthermore, the inter-story drift (Δ_x) is calculated using equations (3) and (4). In addition to the calculation of inter-story drift, the value of permissible inter-story drift on each floor of the building structure is calculated using the equation in Table 1 above. The permissible inter-story drift value will be the maximum limit of the inter-story drift value that occurs on each floor. The calculation of inter-story drift and permissible inter-story drift is shown in Table 6 and Fig. 6 below.

Table 6 Inter-story drift

Story	Δ_x (mm)		h_{sx} (mm)	$\Delta_{a(x)}$ (mm)	Conclusion
	X-direction	Y-direction			
Level 10	17.984	9.846	3400	68.000	Sufficient
Level 9	31.296	19.598	3600	72.000	Sufficient
Level 8	42.742	27.738	3600	72.000	Sufficient
Level 7	52.003	34.310	3600	72.000	Sufficient
Level 6	59.088	39.399	3600	72.000	Sufficient
Level 5	64.106	43.109	3600	72.000	Sufficient
Level 4	67.181	45.558	3600	72.000	Sufficient
Level 3	68.183	46.804	3600	72.000	Sufficient
Level 2	65.113	46.195	3600	72.000	Sufficient
Level 1	41.671	33.250	3600	72.000	Sufficient

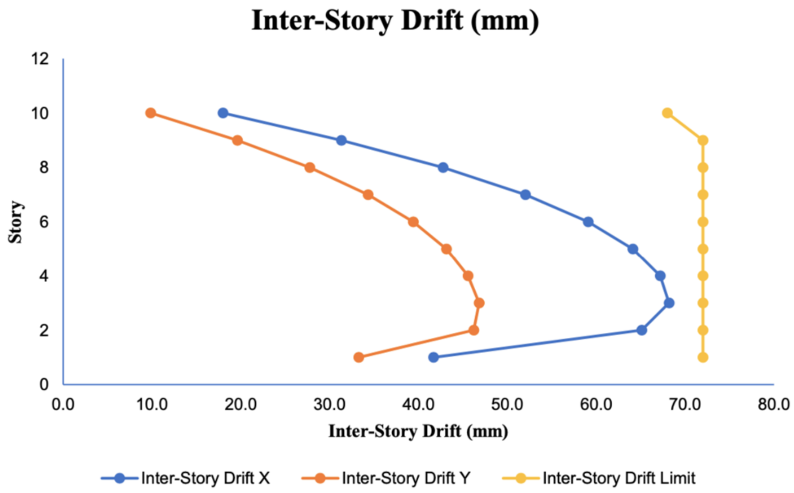

Fig. 6 Inter-story drift of the building

From Table 6 and Fig. 6 above, this indicates that the structure is safe against earthquake loads because the value of the inter-story drift that occurs in X and Y directions at the entire level of the building structure does not surpass the permissible inter-story drift (68.0 mm – 72.0 mm).

5. Conclusions

This study has presented the effect of earthquake forces on the base shear force and inter-story drift values of the high-rise building structure, which is ten-story building structure. According to the results, the following conclusions can be obtained. The value of the base shear force on the analyzed building structure resulting from manual calculation and ETABS analysis has a difference of 3.95% (minor difference), so the base shear force value from the manual calculation can be applied as the design earthquake force in the evaluation of the building structure. The inter-story drift that occurs in X directions at the entire level of the analyzed building structure is 17.984 mm – 68.183 mm and in Y directions at the entire level of the analyzed building structure is 9.846 mm – 46.804 mm. Meanwhile, the permissible inter-story drift in the X and Y directions are 72.0 mm (on the 1st – 9th floors) and 68.0 mm (on the 10th floor). Therefore, the analyzed building structure is concluded capable of withstanding the earthquake forces hitting the structure (safe against earthquake forces).

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