Study comparison P-Delta Effect analysis depends on height variation of the building

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Abstract. Indonesia is an area where three active plates meet, so many areas are prone to earthquakes. To anticipate this and minimize casualties due to earthquakes, earthquake-resistant buildings are needed. Earthquake resistant buildings are the most important thing that needs to be considered, a building structure must be designed to be able to withstand lateral loads such as earthquakes within the limits set by the code/standard. The result of the earthquake load will produce an additional effect on the multi-storey building, namely the P-Delta effect. In this study, the effect of these effects will be analyzed on non-rise buildings and high-rise buildings. Analysis of the P-Delta effect will be calculated on the modeling of three buildings for non-rise buildings (Building models A, B and C) and three high-rise building models (Building models D, E and F) and get the results that the P-Delta Effect has an impact on changes structural performance level in Model E Building (56 meters) from Immediate Occupancy to Life Safety

Keywords: Earthquake, Non-Linear Analysis, P-Delta Effect, Performance Level, Pushover Analysis

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1. Introduction

The death case caused by the earthquake was dominated by collapsed buildings, because a building structure was unable to withstand the earthquake loads that occurred. The need for earthquake-resistant buildings in Indonesia is something that needs to be considered, considering that Indonesia is an earthquake high risk area. A multi-story building structure must be designed to withstand lateral loads such as earthquakes within the limits set by the code or standards. When a structural element as a whole experiences lateral displacement, the building structure will change shape or deform which results in a overturning moment. The eccentricity caused by lateral load that arises produces additional internal moments that can affect the moment of the analysis result. special purposes, such as distinguishing source code text. Right margins should be justified, not ragged. Analysis of the P-Delta Effect needs to be considered because the need for tall buildings from time to time will always increase [1]. In this case the analysis was carried out using the P-Delta Static method according to Indonesia Code Standard (SNI 1726-2019) and P-Delta Dynamic using pushover analysis according to FEMA-356. Due to the complexity of designing the P-Delta Effect, often planning is only done up to the linear static analysis stage, this can later become a cause of structural failure in multi-story buildings [2].

P-Delta Effect

The gravitational load (P) which affects horizontal displacement (Δ) is known as the P-Delta Effect. When the lateral load due to the earthquake acts on a structural element causing displacement or drift (Δ) which results in the eccentricity of the gravity load (P) on the vertical axis of the column, the eccentricity that arises produces additional internal moments that can affect the first-order analysis result moment [2].

The P-Delta Effect that occurs comes from 2 sources, globally the column stem is caused by lateral loads or commonly called the P-Large Delta (P-Δ), and local deformation occurs from within the column rod itself or commonly. called the P-Small Delta (P-δ)

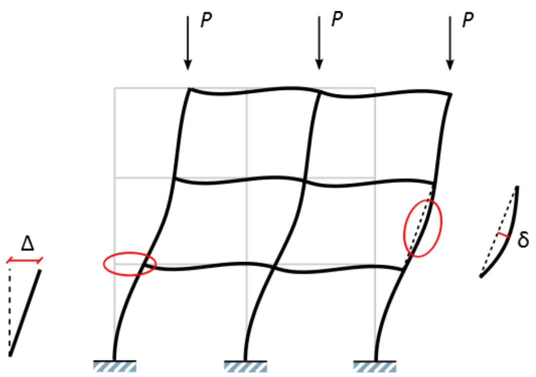

Fig 1: P-Large Delta (P-Δ) & P-Small Delta (P-δ)

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P-Delta Effect (Static)
According to FEMA 356 C3.2.5 Static P-Delta effect occurs due to gravity loads act through the deformation change configuration of a building and results in an increase in lateral displacement [3]. and according to SNI 1726-2019 article 7.8.7, the effect of P-Delta is not required to be calculated if the stability coefficient (ө) is less than or equal to 0.10. [1][2].

P-Delta Effect (Dynamic)
The calculation of the P-Delta Effect is carried out to consider the drift increased. The extent to which the dynamic P-Delta Effect increases displacement according to these following parameters [4].

1. The ratio α of the negative post-yield stiffness to the effective elastic stiffness.
2. The fundamental period of the building.
3. The strength ratio of the building structural system, R.
4. The hysteretic load deformation that effect to each story of the building.
5. The frequency characteristics of the gorund motion.
6. The duration of the strong ground motion.

Based on these parameters, many parameters are involved so it is difficult to consider the dynamic P-Delta Effect using a single modification factor. Thus, the coefficient C3 represents a simplification of the number of parameters considered. The dynamic coefficient C3 and P-Delta Effect coefficients will be taken into account in the non-linear analysis (Non-linear Dynamic Procedure) / pushover analysis [3]. This research will compare the structure behavior with 6 variations of levels in each building model.

2. Literatur Review

Seismic Base Shear
According to SNI 1726-2019/ASCE 7-16 (12.8.1), the seismic base shear force is obtained using the following formula [1].

$$V = C_s W \quad (1)$$

Where:
Cs = Seismic response coefficient
W = Effective seismic weight

Fundamental Period
According to SNI 1726-2019/ASCE 7-16 (12.8.2.1), fundamental period is obtained using the following formula

$$\text{Ta minimum} = C_t.\text{hnx} \quad (2)$$

$$\text{Ta maximum} = C_u.\text{Ta minimum} \quad (3)$$

Where:
Cu = Coefficient upper limit
Ta min = Period's lower limit value

Seismic Acceleration MCER
According to SNI 1726-2019/ASCE 7-16 (11.4.4), Max Spectral Acceleration is obtained using the following formula

$$\text{SMS} = F_a.S_s \quad (4)$$

$$\text{SM1} = F_v.S_1 \quad (5)$$

Where:
Fa = Shot period coefficient at 0.2 period
Ss = Short period spectral response acceleratio
Ss = 1sec period spectral response acceleration.

Spectrum Design Parameter
According to SNI 1726-2019/ASCE 7-16 (11.4.6), Max Spectral Acceleration is obtained using the following formula

$$\text{SDS} = \frac{2}{3}SMS \quad (6)$$

$$\text{SD1} = \frac{2}{3}SD1 \text{ SD1} \quad (7)$$

Where:
SDS = Spectral response design at short period
SD1 = Spectral response design at 1 period

Load Combination

According to SNI 1726-2019/ASCE 7-16 (11.4.6), load combination for seismic load effect is obtained using the following formula

1,4 DL
(8)
1,2 DL + 1,6 LL + 0,5 Lr
(9)
1,2 DL + 1 LL + 1,6 Lr
(10)
1,2 DL + 1 LL + Ey + Eh
(11)
0,9 DL – Ev + Eh
(12)
1,0 DL + 0,7 Ev + 0,7 Eh
(13)
1,0 DL – 0,75 LL + 0,525 Ev + 0,525 Eh
(14)
1,0 DL + 0,7 Ev + 0,7 Eh
(15)

Story Drift

According to SNI 1726-2019/ASCE 7-16 (12.8.6), story drift is obtained using the following formula

$$\delta x = \frac{C_d \ \delta_{xe}}{I_e}$$
(16)

Where:
Cd = Factor of amplification deflection
δxe = Deflection at the location
Ie = Importance seismic factor

P-Delta Effect

According to SNI 1726-2019/ASCE 7-16 (12.8.7), load combination for seismic load effect is obtained using the following formula

$$\theta = \frac{P_x \, \Delta \, I_e}{V_x \, h_{sx} \, C_d}$$
(17)

$$\theta \ max = \frac{0{,}5}{\beta \, C_d} < 25$$
(18)

Where:
Px = Total ertical design at x and above x
Δ = Story drift
Ie = Importance seismic factor
Vx = Seismic base shear
hsx= Story height below level x
Cd = Factor of amplification deflection
β = Ratio of shear demand to shear capacity

Drift Ductility

Ductility ratio is calculated from the maximum displacement value divided by the displacement that occurs at first yielding.

$$\mu\Delta = \frac{\Delta_u}{\Delta_y}$$
(19)

Where:
μΔ = Drift Ductility
Δu = Ultimate Displacement
Δy = Yield Displacement

Pushover Analysis

Pushover analysis is a non-linear static analysis that is carried out to determine the collapse behavior of a building structure by providing a static lateral load pattern then the load will be added step by step.

Pushover analysis is carried out using a 2-dimensional model because it is difficult to find the collapsed load and the failure mechanism when using a 3-dimensional model. Thus, in this study, pushover analysis was carried out using a 2-dimensional model. [6]

The target displacement (δT) is the maximum global displacement (elastic and inelastic) [5] which is calculated using the coefficient factors C0, C1, C2, and C3. The target displacement (δT) in section 3.3.3.3.2 FEMA 356 is obtained by the following equation.

$$\delta T = C0\ C1\ C2\ C3 \frac{Te^2}{4\pi^2} g \quad (20)$$

Where:
Te = Effective fundamental period of the building
δT = Target displacement
C0 = Modification factor SDOF to MDOF
C1 = Modification factor to related expected maximum inelastic displacement
C2 = Modification factor to represent of pinched hysteretic shape
C3 = Modification factor to represent of P-Δ Effect
g = Gravity acceleration

After the performance point is found, the ratio between the maximum displacement that occurs must be compared with the height of the building so that the structure performance level is obtained according to Table 1 (see Table 1).

Table 1. Performance Level

Performance Level	Drift Ratio
IO (Immediate Occupancy)	1%
LS (Life Safety)	2% - 4%
CP (Collapse Prevention)	≥ 4%

3. Building data

This research will compare the structure behavior that occurs due to the P-Delta Effect and without the P-Delta Effect to the height of the building structure with 6 variations of levels in each building model.

Table 2. Building Model Data Information.

	All Building Model
Height between floor	4 meters
X direction	42 meter / 6 meter
Y direction	45 meter / 5 meter
Structure System	SMRF (Special)
Site Class	SD (Stiff Soil)
Risk Level	II
Importance Factor	1,0

3.1. Model and Configuration

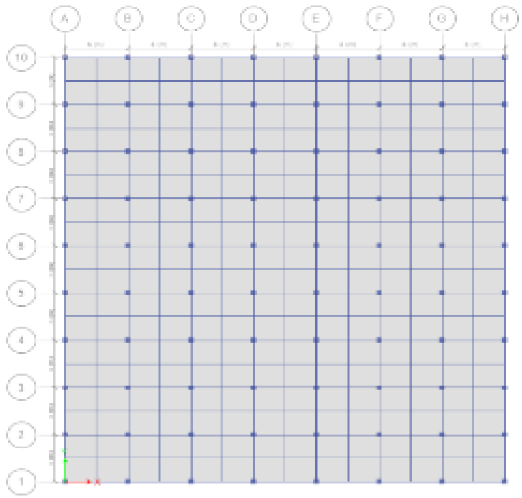

Fig 2: Floor Plan (45 meters x 42 meters)

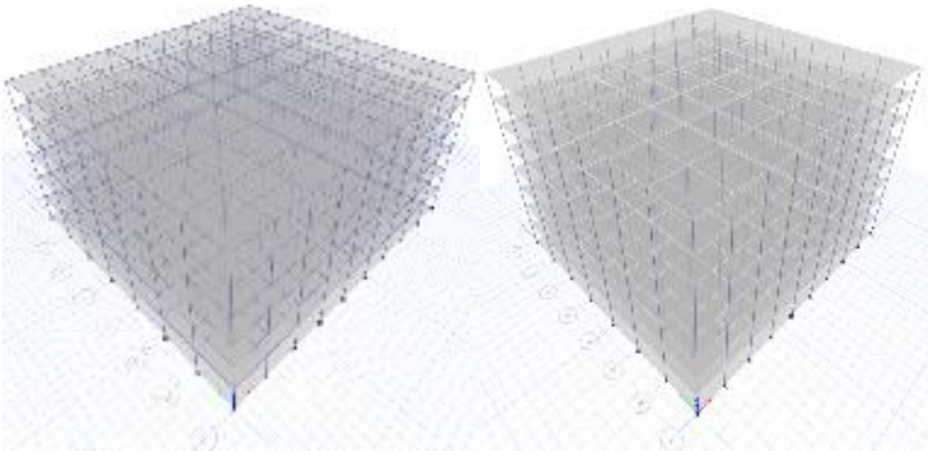

Fig 3: A & B Building Model (24 Meters & 32 meters)

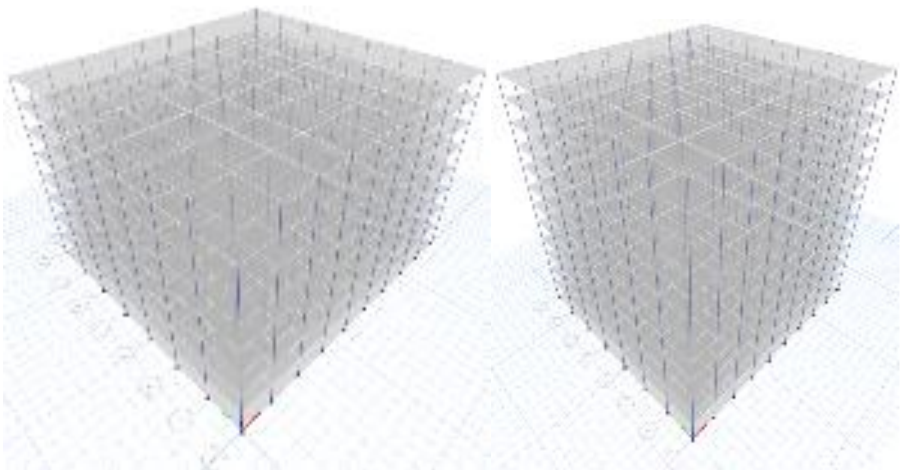

Fig 4: C & D Building Model (40 meters & 48 meters)

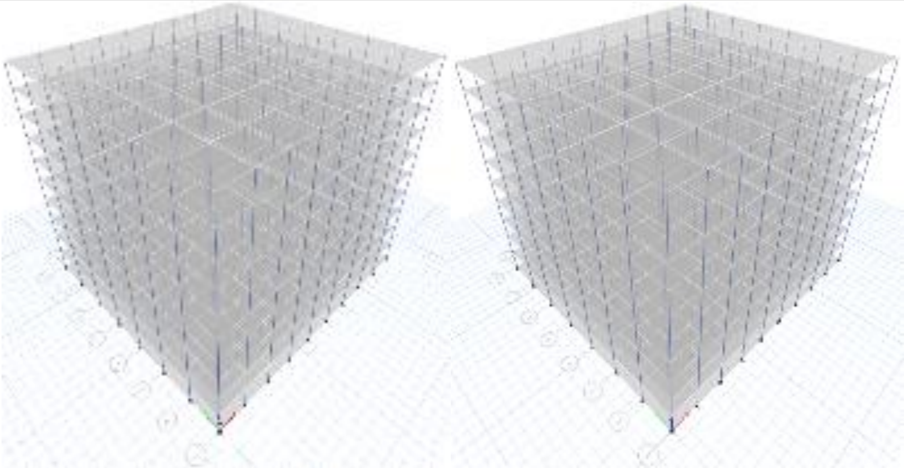

Fig 5: E & F Building Model (56 meters & 64 meters)

Section Properties

The dimensions of the structural elements in each building model are as follows

Table 3. Section Properties.

Structural Element	Dimension
Beam 1 (B1)	450 mm x 250 mm
Beam 2 (B2)	500 mm x 250 mm
Column	500 mm x 500 mm
Floor slab thickness	150 mm

Load Definition

The load which acts on each building model is the same and is defined as follows:

Tabel 4. Load Definition

Gravity Load	
Dead Load (DL)	Auto Calc. - ETABS
Live Load (LL)	1,92 kN/m2
Live Roof (Lr)	0,96 kN/m2
SIDL (Super Impossed Dead Load)	
Ceramic + mortar	1,10 kN/m2
Ducting Mechanical	0,19 kN/m2
Ceiling	0,1 kN/m2
Plafond	0,05 kN/m2
Waterproofing	0,39 kN/m2

Source: ASCE 07-16 Table C3.1-1b.

4. Result and Analysist

Response Spectrum Design

Response spectrum design is calculated based on SNI 1726-2019/ASCE 7-16 with 5% of critical damping.

Table 5. Response Spectrum Design

Response Spectrum Parameter	
Risk Level	II
Importance Factor	1,0
Building Location	Surabaya
Site Class	SD
SS	0,75
S1	0,35
FA	1,20
FV	2,00
SMS	0,90
SM1	0,60
SDS	0,60
SD1	0,47
T0	0,133
TS	0,667
Special Resistant Moment Frame Parameter	
R	8
Ω	3
Cd	5,5

T<T0 the formula is, Sa = SDS (0,4 + 0,6 T/T0)
For T0 ≤ T ≤ Ts the formula is, Sa = SDS
For T ≥ Ts the formula is, Sa = SD1/T

Table 6. Response Spectrum Design T vs Sa

T (dt)	SA (g)	Formulaa	T (dt)	SA (g)	Formula
0.00	0.240	T ≤ T0	2.10	0.190	T ≥ TS
0.10	0.510	T ≤ T0	2.20	0.182	T ≥ TS
0.20	0.600	T0 ≤ T ≤ TS	2.30	0.174	T ≥ TS
0.30	0.600	T0 ≤ T ≤ TS	2.40	0.167	T ≥ TS
0.40	0.600	T0 ≤ T ≤ TS	2.50	0.160	T ≥ TS
0.50	0.600	T0 ≤ T ≤ TS	2.60	0.154	T ≥ TS

T (dt)	SA (g)	Formulaa	T (dt)	SA (g)	Formula
0.60	0.600	T0 ≤ T ≤ TS	2.70	0.148	T ≥ TS
0.70	0.571	T ≥ TS	2.80	0.143	T ≥ TS
0.80	0.500	T ≥ TS	2.90	0.138	T ≥ TS
0.90	0.444	T ≥ TS	3.10	0.133	T ≥ TS
1.00	0.400	T ≥ TS	3.20	0.129	T ≥ TS
1.10	0.364	T ≥ TS	2.10	0.190	T ≥ TS
1.20	0.333	T ≥ TS	2.20	0.182	T ≥ TS
1.30	0.308	T ≥ TS	2.30	0.174	T ≥ TS
1.40	0.286	T ≥ TS	2.40	0.167	T ≥ TS
1.50	0.267	T ≥ TS	3.30	0.121	T ≥ TS
1.40	0.286	T ≥ TS	3.40	0.118	T ≥ TS
1.60	0.250	T ≥ TS	3.50	0.114	T ≥ TS
1.70	0.235	T ≥ TS	3.60	0.111	T ≥ TS
1.80	0.222	T ≥ TS	3.70	0.108	T ≥ TS
1.90	0.211	T ≥ TS	3.80	0.105	T ≥ TS
2.00	0.200	T ≥ TS	3.90	0.103	T ≥ TS

From the results of the table 5 and 6, (see fig 6) the Spectra Acceleration (Sa) vs Period (T) graph for Surabaya, Indonesia.

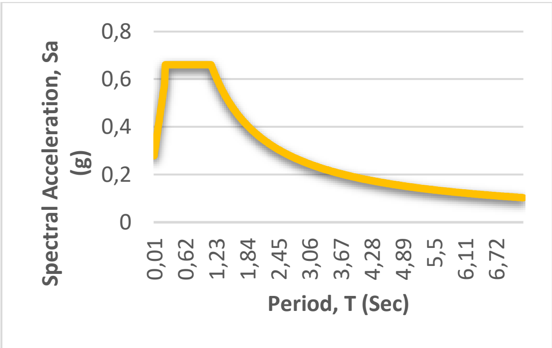

Fig 6: (Surabaya) Response Spectrum Design

Modal Participating Mass Ratio

The mass participation of each building model (A, B, C, D, E, and F) in resisting earthquake loads is regulated in SNI 1726-2019 / ASCE 7-16 (12.9.1), where the combined capital participation of a building structure must participate 100% of the structure mass in resisting earthquake loads.

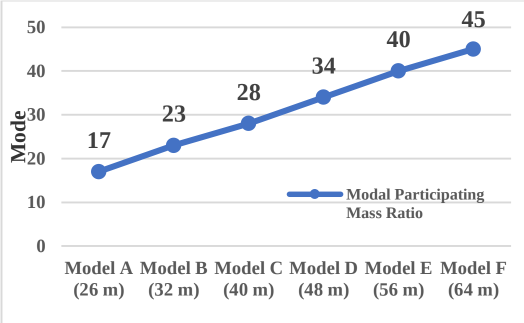

Fig 6: Modal Participating Mass Ratio

According to Fig 6. in each building modeling, it is found that each increase in the height of a building structure has an impact on the increase of mass participation mode. Thus, the mass participation mode of a building structure will increase with increasing height of the building structure.

Story Drift increase caused by P-Δ

Earthquake load which is defined as the lateral load acting on a building structure and interacting with the gravity load results in a change in the internal force on the second order or commonly known as the P-Delta Effect. From the change in the second-order due to the calculation of considering the P-Delta Effect, there is a change in the deviation between floors because the P-Delta Effect provides a story drift increase, the magnification of the deviation that occurs is obtained from the initial deviation multiplied by a scale factor of 1 / (1-Θ) on each inter-story drift, the result of the story drift increase percentage can be seen in Figure 7 and 8

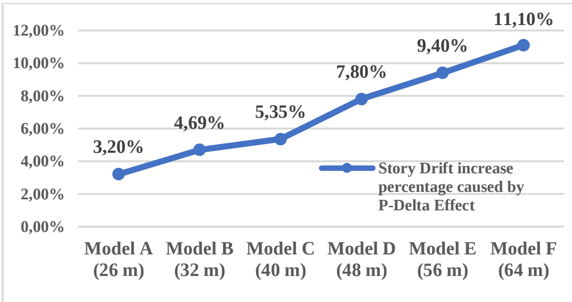

Fig 7: Percentage of Drift Increase (X-axis)

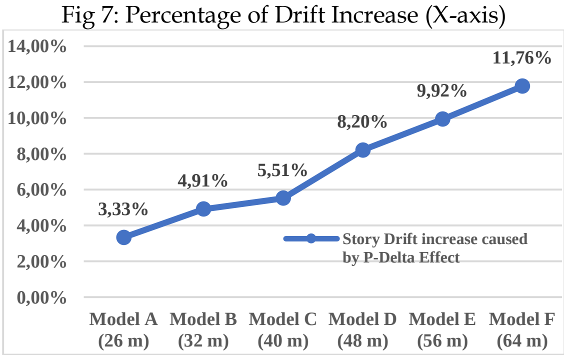

Fig 8: Percentage of Drift Increase (Y-axis)

(see fig 7 and fig 8) the higher a building structure, the greater the influence of the P-Delta Effect in increasing the deviation between floors.

Performance Level

According to FEMA-356, post-earthquake building conditions are categorized into 3 conditions which are IO (Immediate Occupancy), LS (Life Safety), CP (collapse Prevention). To determine the level of performance of a building, it is obtained from the ratio of the maximum displacement compared to the height of the building. The requirement ratio for IO (Immediate Occupancy) performance level is less than 1%, the requirement for life safety is 1% < LS < 2%, while for CP (collapse Prevention) is over than 2%.

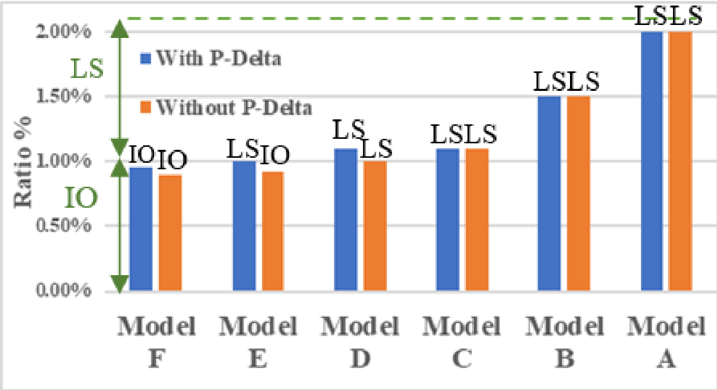

Fig. 11. Performance level X-axis

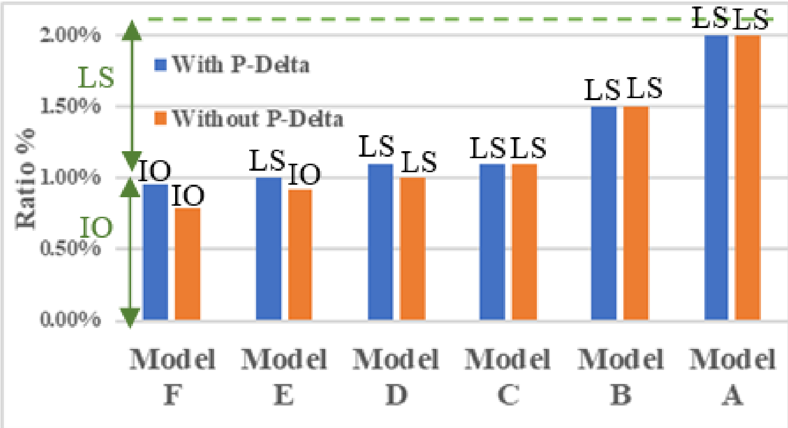

Fig. 12. Peformance level Y-axis

According to fig 11 and fig 12 for 6 building models that have been calculated by pushover analysis, in each direction there is no single building that exceeds the performance level requirements for new building planning required by FEMA 356, which is LS (Life Safety).

5. Conclusion

Based on the analysis and calculations that have been done, the following conclusions are obtained, for 6 building models, there is no single building that exceeds the performance level requirements for new building planning required by FEMA 356, which is LS (Life Safety). The P-Delta Effect that is generated from the pushover calculation does not change the performance level in building modeling with the category of non-high-rise building (under 10 story / 40 meters), while the P-Delta Effect has an impact on building modeling with a high-rise building category (above 10 story / 40 meters) in building E modeling both X-direction pushover and Y-direction pushover from IO (immediate occupancy) to LS (Life Safety).

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