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Application of modified partial capacity design on six-story L-shaped reinforced concrete buildings with variations on elastic columns configurations

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Abstract. Modified Partial Capacity Design (M-PCD) is an alternative design method for seismic-resistant structures. M-PCD adopts the partial side sway mechanism for its failure mechanism where beams and some columns are allowed to develop plastic hinges. This method uses two models for design. The first model simulates a small earthquake occurrence and is used to design beams and plastic columns. The second model simulates a larger earthquake occurrence and damages on the structure. The elastic columns are designed based on the superposition of internal forces from the first and second models, provided that the effects from gravity loads are considered only once. This study focuses on the application of M-PCD on six-story L-shaped reinforced concrete buildings with variations on elastic columns configurations. Nonlinear time history analyses are used to determine the buildings' performance on two earthquake levels (EDRS and MCE_R) and two earthquake directions (0° and 45° rotated earthquake). The results show that the partial side sway mechanism is observed in most of the analyzed structures and drifts are within set boundaries.

1. Introduction

Capacity Design (CD) is commonly used for designing seismic-resistant structures. CD adopts the beam side sway mechanism as its failure mechanism. This is ensured by designing columns stronger than beams (strong column-weak beam). The strong column-weak beam principle causes an excessive requirement for column reinforcements in gravity load dominant buildings. Therefore, Paulay and Priestley [1] proposed an alternative failure mechanism that is the partial side sway mechanism. This failure mechanism allows some columns to develop plastic hinges (plastic columns) and keeps a selection of columns to remain elastic (elastic columns) while ensuring soft story failures doesn't occur to keep the structure safe. Muljati et al. [2] adopted this alternative mechanism and presented a new design method which is named the Partial Capacity Design (PCD). To ensure that the elastic columns don't develop plastic hinges, a magnification factor to scale up the corresponding internal forces of the elastic columns was used. Previous studies on this approach [2-6] showed poor results indicated by some elastic columns still experiencing plastic damages. Pudjisuryadi et al. [7] stated that the bending capacity ratio of beams should be kept to a minimum to avoid plastic damages on the elastic columns since these columns are not design with consideration of the beams' capacity.

Tanaya et al. [8] proposed a modification of PCD to better predict the elastic columns' required strength and named it the Modified Partial Capacity Design (M-PCD). This method uses two models for design. The first model simulates a small earthquake and is used to design beams and plastic columns. The second model simulates a larger earthquake occurrence while also modeling the expected plastic damages. The second model is used to design elastic columns. Early tests show promising results that the expected partial side sway mechanism was observed in most analyzed structures and the drifts are well below the limits set by FEMA 356 [9]. Further development of M-PCD by Pudjisuryadi et al. [10] suggested the second model to not be subjected to full target earthquake and instead is subjected to the difference between target earthquake and design earthquake used in the first model. The change can better predict the elastic columns' required strength because after members develop plastic damages, only the remaining earthquake load (beyond design earthquake) will be distributed according to the structural responses of the second model. The preceding research by Pudjisuryadi et al. [11] proposes a simplified method of the second model by applying a modification factor to the full length of members expecting plastic damage. In this research, to further investigate the performance of Pudjisuryadi et al. [10] M-PCD, three six-story L-shaped reinforced concrete buildings with variations on elastic columns configurations are designed and analyzed.

2. Modified-Partial Capacity Design

M-PCD's design models represents two different states. The first model represents the undamaged structure state when a small earthquake occurs (see Figure 1). This model uses an R value of 8.0 (DER_{80}), the upper limit of partially ductile structures, from SNI 1726:2002 [12]. The second model represents the already damaged structure and simulates a larger earthquake (see Figure 2). This model uses the difference of R values between 1.6, an R value for fully elastic structures, and 8.0 (DER_{16}-DER_{80}). The beams and plastic columns are designed using the internal forces from the first model, while the elastic columns are designed using the superposition of internal forces from the first and second models and the effects of gravity loads are taken into account only once. Two levels of earthquakes, Elastic Design Response Spectrum (EDRS) and Maximum Considered Earthquake (MCE_R) are used to analyze the performance of M-PCD's design (see Figure 3). However, it should it be noted that these earthquakes are much larger than the earthquakes used for design.

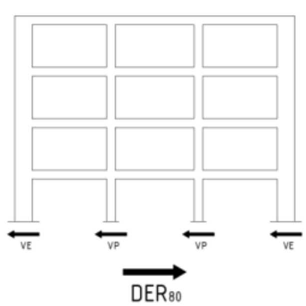

Figure 1. M-PCD's first model.

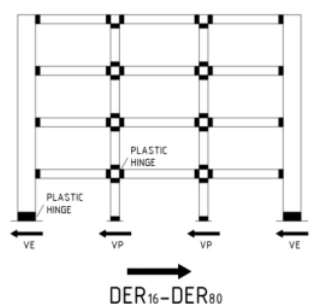

Figure 2. M-PCD's second model.

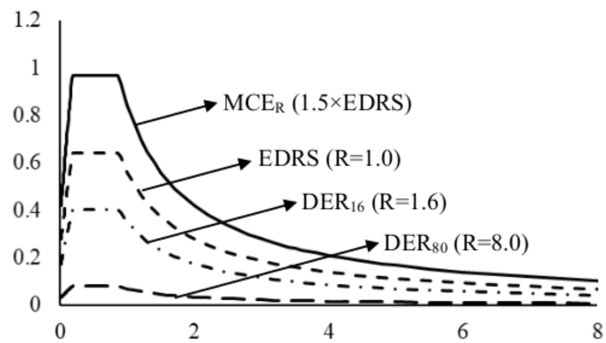

Figure 3. Earthquake levels used for the analyses.

The expected damages on the structure in the second model, e.g., beams, plastic columns, and base of elastic columns, are modeled by reducing the flexural stiffness along the plastic hinge areas. The ratio of reduced stiffnesses to its initial values can be determined from typical moment rotation curve generated by sectional analysis. The length of the plastic hinge areas is calculated using Paulay and Priestley's equation [1], as shown in equation (1) where l_p is the plastic hinge length; l is the member's length; d_b is the longitudinal rebar diameter; f_y is the yield strength of the longitudinal rebar. Alternatively, the plastic hinge length can be approximated as 0.5 multiplied by the member's section depth. In this research, equation (1) was used.

$$l_p = 0.08l + 0.022d_b f_y \quad (1)$$

3. Models and Design of Structures

Three structure configurations and their typical elevation view (see Figures 4 and 5) are used in this research. SAP2000 software [13] was used to model the structures. The structures are assumed to be in Surabaya resting on site class E soil and intended as office buildings. Besides the self-weight of the structure, the applied gravity load is in accordance with SNI 1727:2020 [14], as shown in Table 1. The seismic load is in accordance with SNI 1726:2019 [15]. 100% seismic load is applied in the Y direction and 30% in the X direction. The elements are design using SNI 2847:2019 [16], dimensions and properties are shown in Table 2. Rebar and bending capacity ratios are shown in Tables 3, 4, and 5.

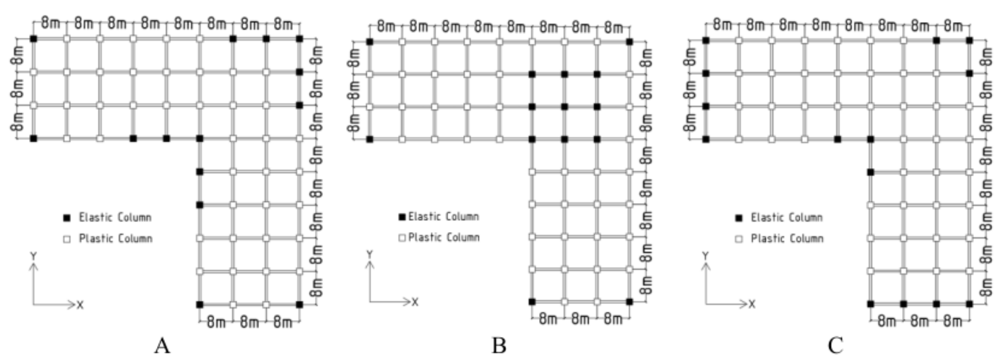

Figure 4. Plan view for the configurations of elastic columns for each structure.

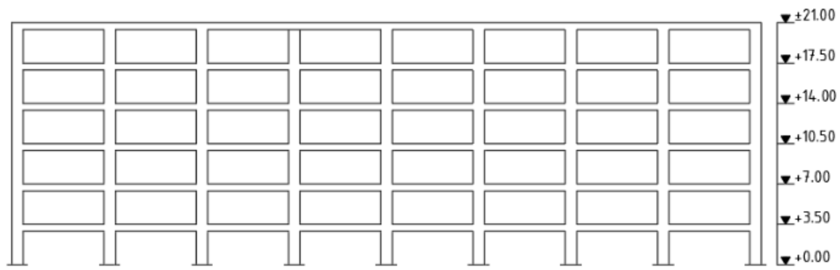

Figure 5. Elevation view of the six-story structures.

Table 1. Gravity loads.

Story	Dead Load (kN/m^2)	Live Load (kN/m^2)	Wall Load (kN/m)
6	0.88	0.96	-
5	0.88	2.40	8.92
4	0.88	2.40	8.92
3	0.88	2.40	8.92
2	0.88	2.40	8.92
1	0.88	2.40	8.92

Table 2. Dimensions and properties of elements.

Story	Elastic Column	Plastic Column
6	600×600	350×350
5	650×650	400×400
4	700×700	400×400
3	700×700	450×450
2	700×700	450×450
1	700×700	500×500

Beam: 300×600 Secondary Beam: 250×500
Slab thickness: 120 mm
Concrete compressive strength, f_c' = 30 MPa
Yield strength of longitudinal reinforcement, f_y = 400 MPa
Yield strength of transversal reinforcement, f_{yt} = 400 MPa

Table 3. Elastic column rebars and capacity ratios.

Story	Longitudinal Rebar	Bending Capacity Ratio			Transversal Rebar
		A	B	C	
1	28D25	0.886	0.911	0.763	3D13-90
2	44D25	0.771	0.941	0.732	3D13-110
3	44D25	0.814	0.977	0.776	3D13-110
4	40D25	0.774	0.951	0.763	3D13-110
5	36D25	0.835	0.954	0.804	3D13-120

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Table 4. Plastic column rebars and capacity ratios.

Story	Longitudinal Rebar	Bending Capacity Ratio			Transversal Rebar
		A	B	C	
1	12D25	0.966	0.986	0.911	3D10-120
2	16D25	0.899	0.912	0.885	3D10-110
3	12D25	0.921	0.932	0.903	3D10-110
4	12D25	0.876	0.885	0.867	3D10-100
5	8D25	0.823	0.827	0.876	3D10-100
6	8D25	0.745	0.884	0.751	3D10-80

Table 5. Beam rebars and capacity ratios.

Story	Rebar Position	Longitudinal Rebar	Bending Capacity Ratio			Transversal Rebar
			A	B	C	
1	Top	7D22	0.799	0.816	0.767	2D10-130
	Bottom	4D22				
2	Top	8D22	0.803	0.816	0.758	2D10-130
	Bottom	4D22				
3	Top	8D22	0.812	0.822	0.767	2D10-130
	Bottom	4D22				
4	Top	7D22	0.885	0.895	0.837	2D10-130
	Bottom	4D22				
5	Top	7D22	0.817	0.822	0.785	2D10-130
	Bottom	3D22				
6	Top	5D22	0.767	0.814	0.774	2D10-130
	Bottom	3D22				

4. Structural Performance

The structures' performance was analyzed using Nonlinear Time History Analysis (NLTHA) using SAP2000. EDRS and MCE_R, are used for the analyses. The ground motion used was the 1940 El Centro earthquake spectrally matched in the time domain to Surabaya site class E response spectrum in accordance with SNI 1726:2019 [15] on both levels. Its directions are shown in Figures 6 and 7. The ground motion was obtained from PEER. H1 is the North-South component of the earthquake, while H2 is the East-West component.

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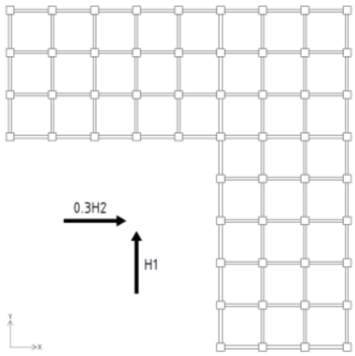

Figure 6. 0° earthquake direction.

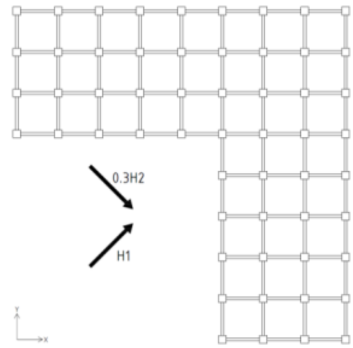

Figure 7. 45° rotated earthquake direction.

4.1. Plastic hinge results

SAP2000 [13] uses a color-based way to categorize damages on the modeled hinges as shown in Figure 8. B represents yield state and C represents ultimate yield state, while IO (Immediate Occupancy), LS (Life Safety), CP (Collapse Prevention) represents the states between B and C. D represents the structure only having residual strength and E represents complete structure failure.

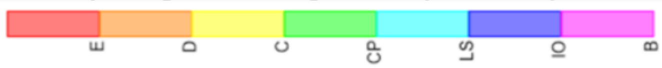

Figure 8. Damage index of modeled hinges.

The analyses showed that M-PCD can produce structures with good performance, tested on the 0° earthquake on both earthquake levels, as shown in Figure 9. There are no plastic hinge levels above FEMA 356' standards [9], life safety (LS) level for EDRS and collapse prevention (CP) level for MCE_R. However, the tests on the 45° rotated, MCE_R level earthquake produced inadequate results. Plastic hinge levels above the collapse prevention level occurred on structures A and B (see red box marks in Figure 10). In terms of number of plastic hinges that appeared and level, the C configuration is better than the others. It is observed that the 0° earthquake impact the beams more than the plastic columns, while the 45° rotated earthquake impact the plastic columns more (see Figure 11).

4.2. Drift results

Drifts occurred on all structures are far below limitations set by FEMA 356 [9]. These limitations are 2% for EDRS and 4% for MCE_R. The drift results for every configuration have very similar magnitude and shape for parallel earthquake levels and directions, and maximum values happened at similar time step values around 2.5 to the 5 second mark, when the maximum acceleration of the 1940 El Centro earthquake occurs. The drift results are shown in Figure 12. Although, the drift results are similar, the C configuration is better than the others, it has the smallest maximum drift values in every analyses.

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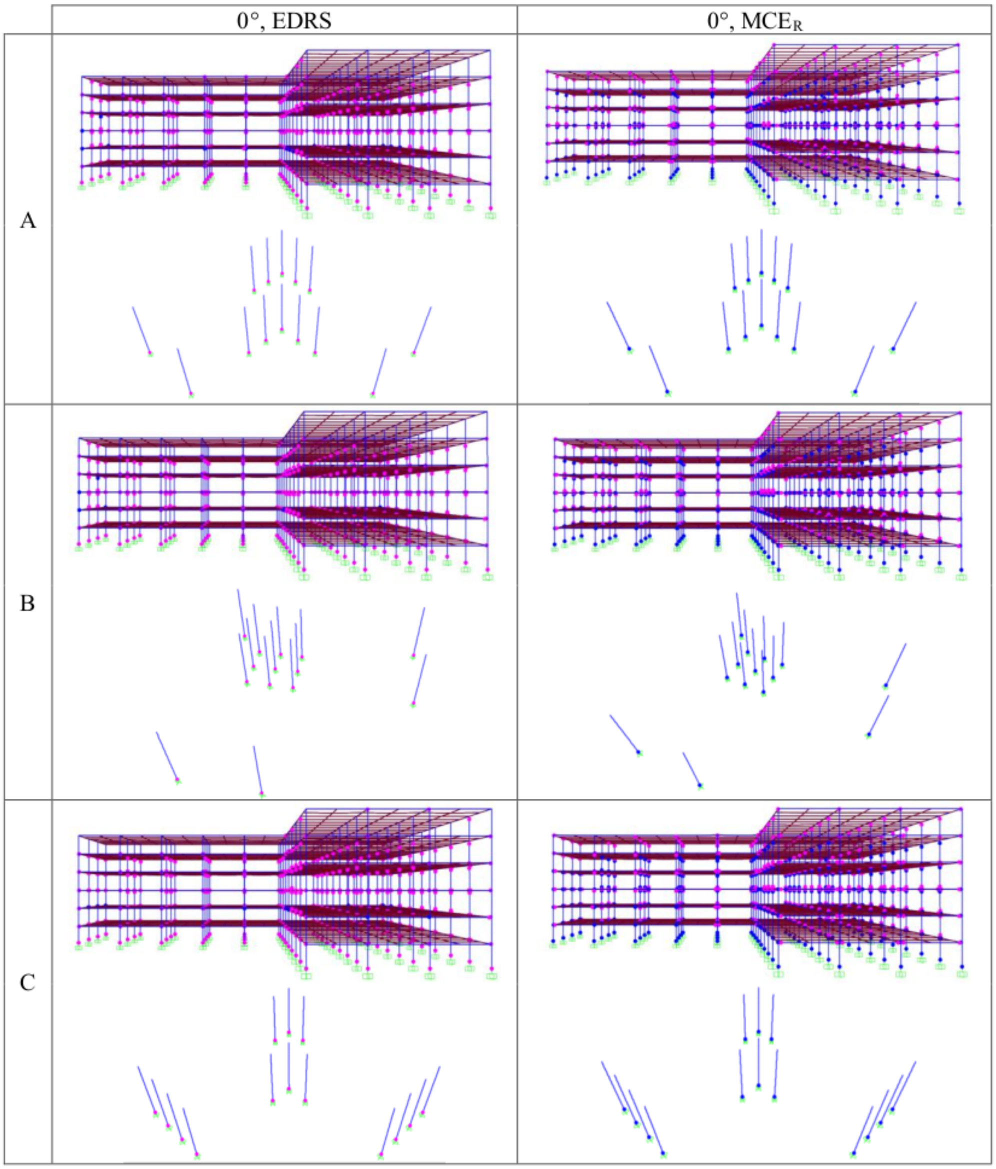

Figure 9. Plastic hinge results for 0° earthquake on EDRS and MCE$_R$ levels.

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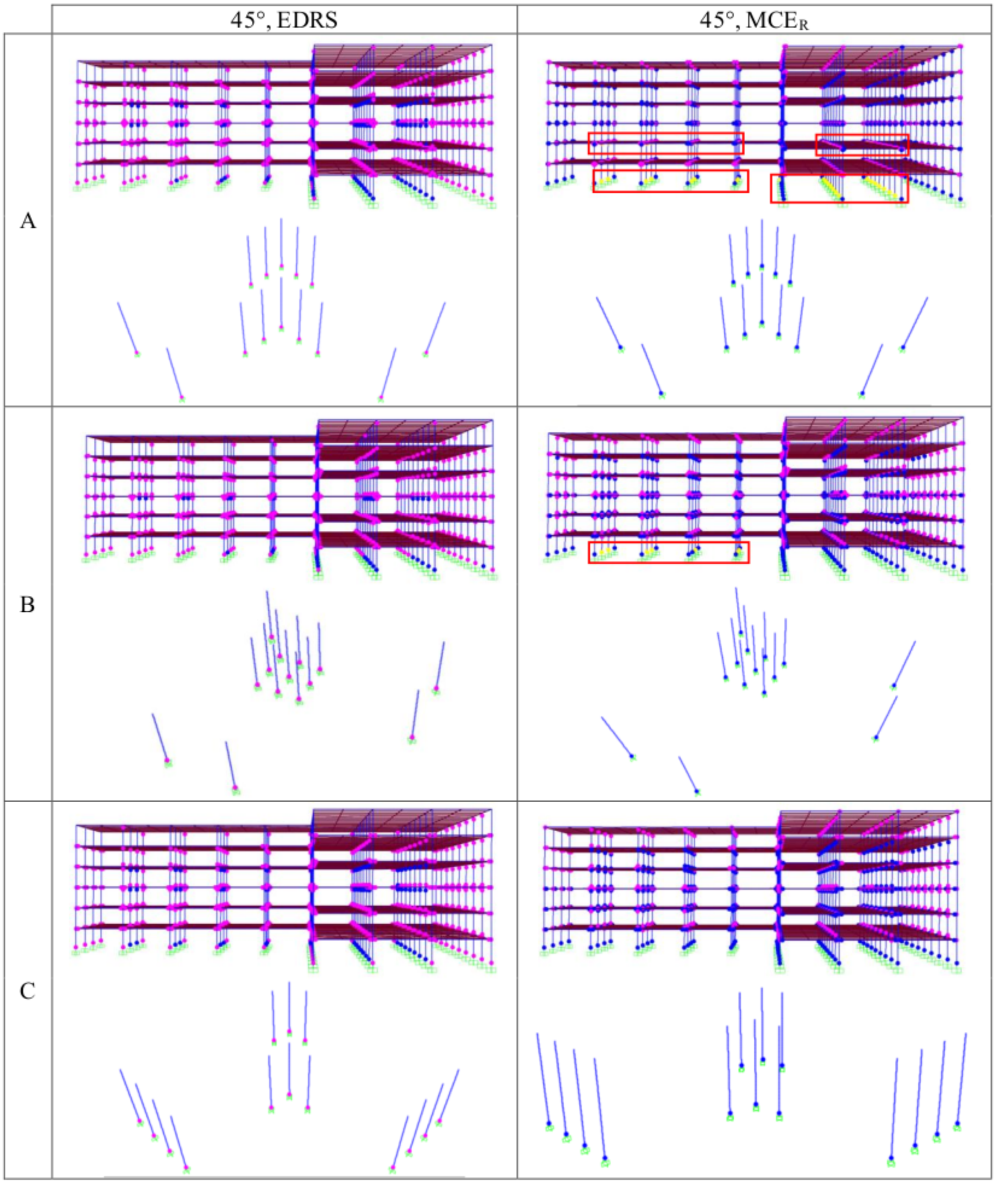

Figure 10. Plastic hinge results for 45° earthquake on EDRS and MCE_R levels.

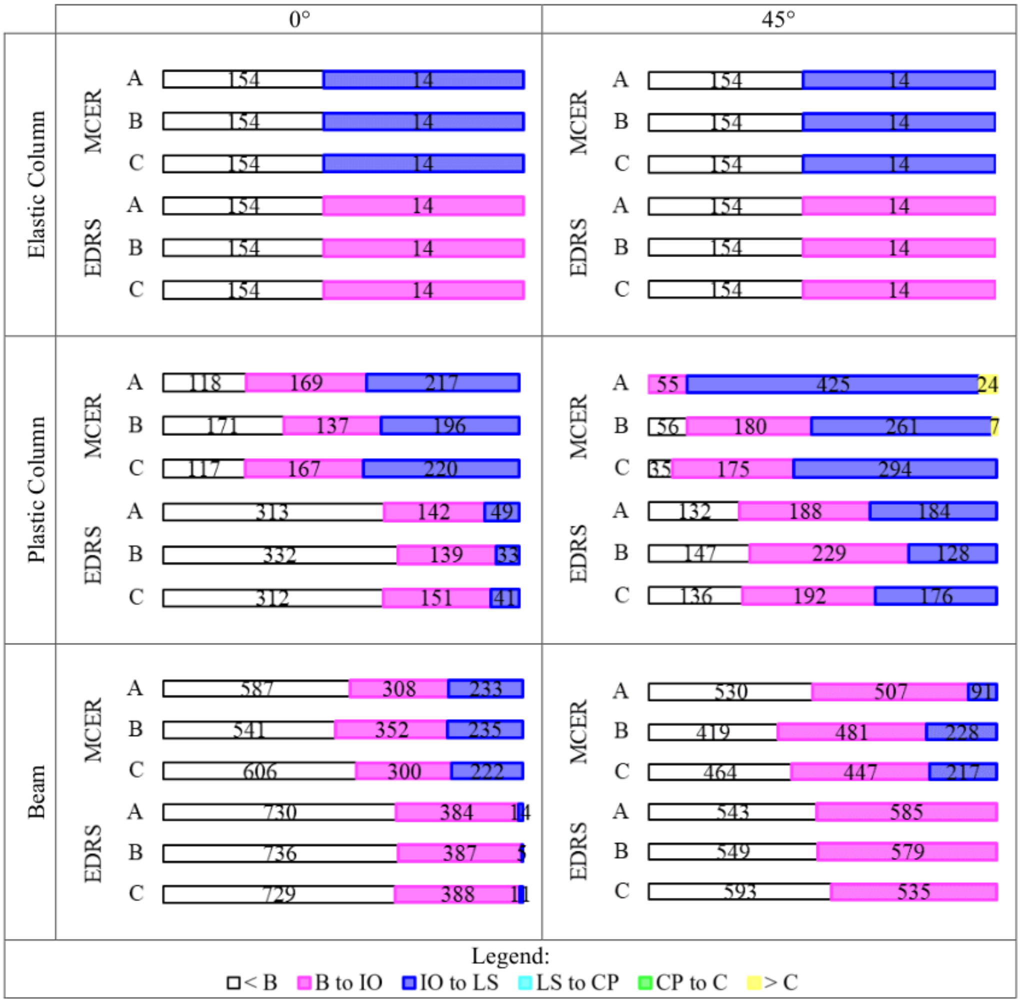

Figure 11. Number of plastic hinges.

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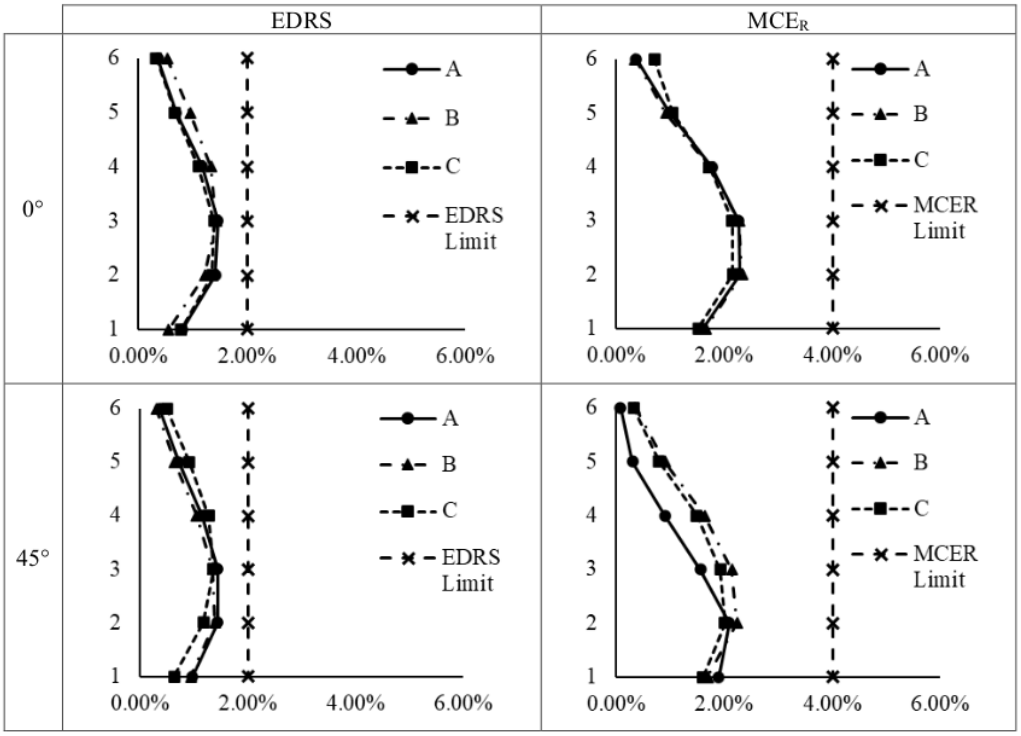

Figure 12. Drift results.

5. Conclusion

Based on the research done on the three configurations, L-shaped reinforced concrete structures (A, B and C) designed using M-PCD can produce good performances and can undergo target earthquake with stable partial side sway mechanism. Comparing the three configurations, C has the best performance out of the others, based on plastic hinge and drift results. Drifts are similar in all three configurations and is far below limitations set by FEMA 356. However, exceptions for configurations A and B, based on the plastic hinge results (exceeded level limits), still occur in the 45° rotated, MCE_R level earthquakes, but it should be noted that the design process considers only 0° earthquake effects and the MCE_R level is much higher than the earthquakes used for design. Solutions that can be proposed are considering rotated earthquakes and modifications to the R value in the design process. Nevertheless, further study and development are still needed for this alternative design method.

References

[1] Paulay T and Priestly M J N 1992 Seismic Design of Reinforced Concrete and Masonry Buildings (New York) pp 141-142

[2] Muljati I and Lumantarna B 2007 *Proc. of the 19th Australasia Conf. on the Mechanics of Structures on Materials* (ACMSM19) (New Zealand, Christchurch) pp 409-414

[3] Muljati I and Lumantarna B 2008 *Proc. of The Eleventh East Asia-Pasific Conf. on Structural Engineering and Construction* (EASEC-11) (Taipei)

[4] Muljati I and Lumantarna B 2011 *The Twelfth East Asia-Pasific Conf. on Structural Engineering and Construction* (EASEC-12) (Hong Kong) **14** pp 220-226

[5] Muljati I and Lumantarna B 2011 *2nd International Conf. on Earthquake Engineering and Disaster Mitigation* (ICEEDM) (Surabaya)

[6] Herryanto H, Tanaya L S and Pudjisuryadi P 2021 *IOP Conf. Series :Earth and Environmental Science* (Surabaya) **907** p 012007

[7] Pudjisuryadi P, Lumantarna B, Teddy S, and Wijoyo H 2011 *The 3rd International Conf. of European Asian Civil Engineering Forum* (EACEF) pp 145-151

[8] Tanaya L S, Herryanto H, and Pudjisuryadi P 2021 *IOP Conf. Series: Earth and Environmental Science* (Surabaya) **907** p 012003

[9] Federal Emergency Management Agency 356 2000 *Prestandard and Commentary for the Seismic Rehabilitation of Buildings* (Washington, D.C.) p 14

[10] Pudjisuryadi P, Wijaya F, Tanuwijaya R, Prasetyo B C, and Lumantarna B 2021 Performance of Six- and Ten story Reinforced Concrete Buildings Designed by Using Modified Partial Capacity Design (M-PCD) Method with 70% Shear Force Ratio *Civil Engineering Dimension* **23** pp 131-137

[11] Pudjisuryadi P, Lumantarna B, Wijaya F, Aphrodita C, Jessica A, Karyanto Y, and Theodora M K 2022 Application of Modified-Partial Capacity Design on 6- and 15-story Square Buildings with Variation in numer of Elastic Columns *Civil Engineering Dimension* **24** pp 46-53

[12] Badan Standarisasi Nasional 2002 SNI 03-1726:2002 *Standar Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung* (Jakarta) p 15

[13] CSI 2017 CSI *Analysis Reference Manual for SAP2000, ETABS, SAFE, and CsiBridge, Computer & Structure*

[14] Badan Standarisasi Nasional 2020 SNI 03-1727:2020 *Beban Minimum untuk Perancangan Bangunan Gedung dan Struktur Lain* (Jakarta) p 27

[15] Badan Standarisasi Nasional 2019 SNI 03-1726:2019 *Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Non Gedung* (Jakarta)

[16] Badan Standarisasi Nasional 2019 SNI 03-2847:2019 *Persyaratan Beton Struktural untuk Bangunan Gedung dan Struktur Lain* (Jakarta)

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