Development and Implementation of Modified Partial Capacity Design (M-PCD) with Nonlinear Structural Analysis on Regular Buildings

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Development and Implementation of Modified Partial Capacity Design (M-PCD) with Nonlinear Structural Analysis on Regular Buildings

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Abstract. The Modified Partial Capacity Design (M-PCD) method is a development of the Partial Capacity Design (PCD) method aimed at improving seismic design of structures that allows partial side sway mechanism. M-PCD ensures some columns to remain elastic by using two design models: Model 1 which is subjected to earthquake with response modification coefficient, R=8 for beams and plastic columns design, and Model 2 which is subjected to earthquake with R=1 for elastic columns design. This study evaluates the effectiveness of the proposed M-PCD method, particularly in comparison to the M-PCD method by Santoso and Wiranata (2024), focusing on improvement of elastic columns design. Structural performance evaluation is conducted using the Nonlinear Dynamic Procedure (NDP) or time history analysis with a Risk-Targeted Maximum Considered Earthquake (MCE_R) level. Results indicate that the structure designed using the previous M-PCD method tends to reflect partial side sway mechanism more than the proposed M-PCD method unexpectedly. In addition, FEMA 273 criteria regarding plastic hinge damage levels in plastic columns and beams are still exceeded, but FEMA 273 drift criteria are met in all structural models. One possible reason for the excessive damage levels is that the assumption of ductility possessed by the structure is not as high as conventional special moment resisting frame (R=8). Logically, the structure will experience plastic damage more than expected.

Keywords: Elastic Columns, Modified Partial Capacity Design, Partial Side Sway Mechanism, Plastic Columns.

1 Introduction

In earthquake-prone areas, the design of earthquake-resistant buildings is mandatory to ensure human safety. The development of seismic design methodologies like Capacity Design (CD), Partial Capacity Design (PCD), and Modified Partial Capacity Design (M-PCD) aims to enhance building resilience. CD emphasizes the strong column-weak beam principle, ensuring beams failure before columns to prevent catastrophic building collapse. However, this method is time-consuming as it requires beam design first.

Moreover, according to Paulay and Priestley [1], CD method is not efficient to be applied on gravity-dominated structure, as the strong column-weak beam concept produces overdesigned columns. Thus, partial side sway mechanism was introduced, where plastic hinges are allowed at some columns. In other words, this mechanism ensures that there are some columns that remain elastic in each story which prevent soft story failures. This method simplifies the design of beams and columns so that they can be done simultaneously but has limitation in the use of effective magnification factor. However, PCD has not been widely used for practical design due to some drawbacks from previous study [2]. PCD has also been refined with an alternative approach using predicted post-elastic story shear distribution, but still produced unexpected plastic hinges at elastic columns [3]. M-PCD further refines this issue by utilizing two models: one for beams and plastic columns design, and another for adjusting stiffness for more accurate force redistribution [4].

Even though there are improvements, some experiments showed challenges in meeting FEMA 273 [5] conditions under Risk-Targeted Maximum Considered Earthquake (MCE_R) level. The original concept of M-PCD has been tested in various structural configurations and scenarios and still shows inconsistent results [6,7,8]. Recent research by Santoso and Wiranata (2024) explored M-PCD method using lumped plasticity approach for more accurate plastic hinge modelling [9]. This method allowed automatic damage detection and force redistribution which is more accurate compared to previous plasticity models using stiffness adjustment [4,6,7,8], but still had issue with elastically designed column bases. This study proposes iterative adjustments and testing under MCE_R level for elastically designed columns, aiming for a more efficient and realistic design, accommodating the worst allowable damage within the partial side sway mechanism.

The proposed new approach is named MPCD-1, while MPCD-2 is used for the previous version by Santoso and Wiranata (2024), where the results of both will then be compared. The key difference lies in the exterior base columns: MPCD-1 designs them to behave plastically, while MPCD-2 designs them to behave elastically, so that all hinges should be formed at selected locations during strong earthquake as illustrated in Fig. 1.

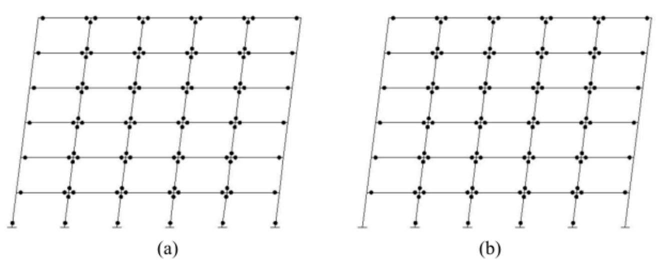


Fig. 1. Allowable plastic hinge configurations in: (a) MPCD-1 (b) MPCD-2.

2 Modelling

The structural modelling is performed using SAP2000 for 6-story rectangular buildings with specifications and gravity loads stated in Table 1, representing typical office buildings scenario in general. The building has a typical floor plan with 5 bays depicted in Fig. 2. The beams and columns are grouped based on their location on the floor plan. Perimeter columns are designed to remain elastic under MCE_R level, while beams and interior columns are allowed to form plastic hinges. As plastic hinges form during strong earthquake, seismic forces are expected to redistribute to the columns that remain elastic so that the entire building does not collapse due to soft story mechanism. Two structural models subjected to different seismic loads are used to design the structural elements.

Table 1. Building specifications and gravity loads for structural modelling.

Parameter	Value
Number of stories	6
Building plan dimension	30 m x 30 m
Building area per story	900 m^2
Column to column distance	6 m
Building height	24 m
Slab thickness	150 mm
Concrete compressive strength	30 MPa
Longitudinal reinforcement yield strength	420 MPa
Transversal reinforcement yield strength	420 MPa
Super-imposed dead load	1.5 kN/m^2
Live load	2.4 kN/m^2
Nonstructural wall load (exterior beam only)	10 kN/m

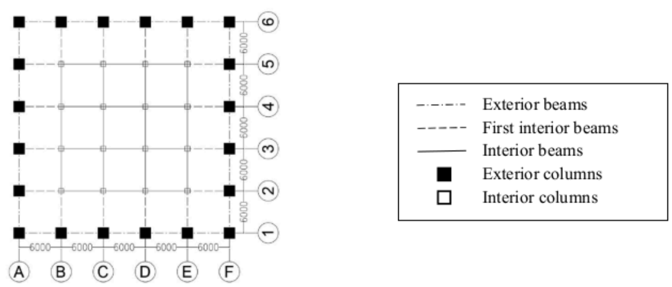


Fig. 2. Typical floor plan.

In Model 1, elements which may behave inelastically during strong earthquake are designed under Design Basis Earthquake (DBE) with R=8, including beams, interior columns, and exterior base columns for MPCD-1, while only beams and interior columns for MPCD-2. The material properties are still assumed to be in linear conditions under DBE level. Since M-PCD allows plastic hinges at some columns, the design process in Model 1 is carried out without considering strong column-weak beam requirement. The seismic load is obtained from the Indonesian earthquake hazard map for Surabaya city with site class E which is assigned as spectrum response.

Model 2 focuses on designing the remaining columns in the exterior area under MCE_R level using nonlinear time history analysis, with no response modification coefficient to ensure them to remain elastic. The ground acceleration used for nonlinear time history analysis is a spectrally matched acceleration component of El Centro 1940. The selection of ground motion is not critical as it is used for comparative study, so the exact results are not the main interest. The entire buildings are analyzed using lumped plasticity approach where the expected plastic hinges are placed at both ends of beams and plastic columns to capture the nonlinear behavior of structure elements, in accordance with ASCE 41-17 [10]. Elastic columns are iteratively designed with longitudinal reinforcement ranging from 1% to 6%, in compliance with SNI 1726:2019 [11].

3 Design

The design of exterior columns using the proposed method, MPCD-1, is given in Table 2. The reinforcement design is attempted to be as optimal as possible with a capacity ratio close to 1.00. This parameter defines the ratio of the combined axial-bending force demand to its capacity. It should be noted that MPCD-1 allows exterior base columns to form plastic hinges which results in a reduced amount of flexural reinforcement at Story 1. To measure the effectiveness of the proposed method, the design of exterior columns is also carried out using the previous method, MPCD-2, given in Table 3. Unlike MPCD-1, MPCD-2 does not allow exterior base columns to form plastic hinges, resulting in larger exterior columns dimension throughout the stories, thereby increasing material usage and construction costs.

Table 2. Exterior columns design using the MPCD-1 method.

Story	Dimension (mm x mm)	Flexural reinforcement	Reinforcement ratio (%)	Capacity ratio
1	700 x 700	8D29	1.08	0.454
2	700 x 700	36D32	5.91	0.901
3	650 x 650	28D29	4.38	0.987
4	600 x 600	32D29	5.87	0.905
5	600 x 600	24D29	4.40	0.960
6	500 x 500	22D29	5.81	0.915

Table 3. Exterior columns design using the MPCD-2 method.

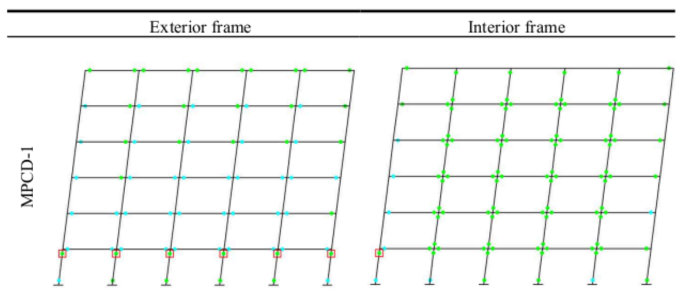
Story	Dimension (mm x mm)	Flexural reinforcement	Reinforcement ratio (%)	Capacity ratio
1	1150 x 1150	54D40	5.13	0.93
2	1000 x 1000	38D40	4.78	0.93
3	850 x 850	44D32	4.90	0.927
4	800 x 800	32D32	4.02	0.934
5	700 x 700	50D25	5.01	0.929
6	650 x 650	50D22	4.50	0.928

4 Result

Both structure models designed using MPCD-1 and MPCD-2 methods are evaluated against MCE_R level with nonlinear time history analysis. The structural performance assessed includes structural collapse mechanism, hinge state, and story drift.

To observe structural collapse mechanism, Fig. 3 shows plastic hinge locations in exterior and interior frames. The color indicator refers to hinge state as depicted in Fig. 4. The hinge state A to B shows elastic zone, state B to C shows post-yield zone, state C to D shows strength degradation, while state D to E shows residual strength.

Plastic hinges are formed in beams and interior columns as expected in partial side sway mechanism; however, some plastic hinges also take place at exterior columns (box marked), thereby increasing possibility of unsafe soft story mechanism. This may happen because of inadequate capacity of plastic elements in dissipating seismic forces during MCE_R level, so that the excess seismic force runs to the exterior columns.



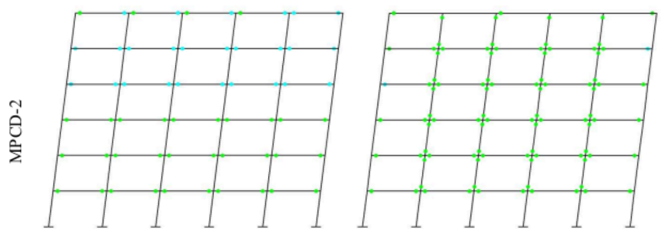
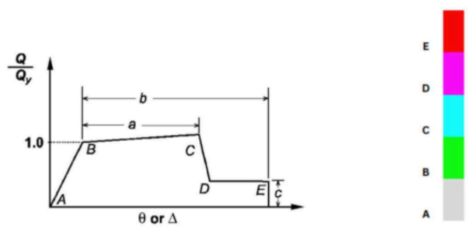


Fig. 3. Plastic hinge configuration.



(a) (b)

Fig. 4. Hinge state: (a) generalized force-displacement relation [10] (b) color indicator.

To find out more details about the damage level for each structural element, Table 4 shows number of hinges and their state in structural models designed using both MPCD-1 and MPCD-2 methods. All exterior columns in MPCD-2 remain elastic as planned, but unexpectedly some exterior columns in MPCD-1 exceed the yield point and even further to strength degradation. In addition, all beams and interior columns in MPCD-1 and MCPD-2 are allowed to behave inelastically, but it turns out that some of them exceed the ultimate point, leading to strength degradation.

Table 4. Number of hinges based on the hinge state.

Hinge state	MPCD-1			MPCD-2		
	Beam	Interior column	Exterior Column	Beam	Interior column	Exterior column
A to B	79	0	205	64	32	241
B to C	519	184	27	576	161	0
C to D	123	9	9	81	0	0

Fig. 5 shows the story drift of buildings designed using both MPCD-1 and MPCD-2 methods. Both models meet the criteria set by FEMA 273 [5], at 4% for MCE_R level. On most stories, the model designed using MPCD-2 has smaller story drift than the model designed using MPCD-1 due to the higher lateral stiffness caused by the larger dimensions of the exterior columns.

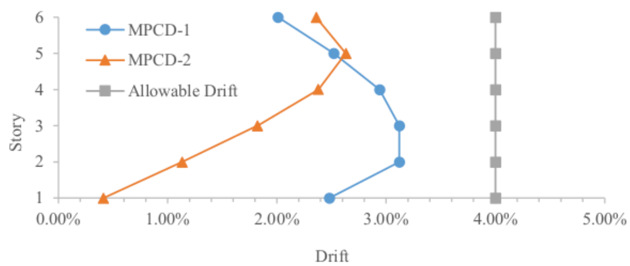


Fig. 5. Story drift.

5 Summary

The MPCD-1 method results in a more economical column reinforcement design compared to MPCD-2 because it successfully forms plastic hinges at the base columns. However, nonlinear time history analysis for the building designed using MPCD-1 shows that the failure mechanism does not reach the partial side sway mechanism because some hinges are formed in the exterior columns. Although the story drift results for both methods meet the FEMA 273 criteria, both methods fail to meet the beam capacity requirements as the hinge states exceed the ultimate point during the MCE_R test. To better accommodate this issue, better determination of R value should be a priority for future M-PCD method development before being widely proposed for practice. Overall, the proposed method, MPCD-1, has not provided optimal results because several requirements still exceed the specified limits.

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