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Modified Partial Capacity Design (M-PCD): achieving partial sidesway mechanism by using two steps design approach

L S Tanaya[1,2], H Herryanto[1] and P Pudjisuryadi[1]

[1] Civil Engineering Department, Petra Christian University, Surabaya, Indonesia

[2] Corresponding author: levintanaya@gmail.com

Abstract. Partial Capacity Design (PCD) has been developed by using magnification factor to keep some columns undamaged during major earthquake. By doing so, the structures will experience the partial side sway mechanism which is also stable, instead of the beam sidesway mechanism. However, in some cases, structures designed by PCD method failed to show the partial side sway mechanism since unexpected damages were still occurred at some columns. In this research, modification of PCD method is proposed by using two structural models in the design process. The first model is used to design beams and columns which are allowed to experience plastic damages, while the second model is used to design columns which are intended to remain elastic when the structure is subjected to a target earthquake. Two nominal earthquakes corresponding to Elastic Design Response Spectrum (EDRS) level with seismic modification factors (R) of 8.0 and 1.6 are used in the first and second structural models, respectively. It should be noted that the second model is identical to the first model except that the stiffnesses are reduced for elements to simulate potential plastic damages. This proposed method is applied to symmetrical 6 and 10 storey buildings with seismic load according SNI 1726:2012 and with soil classification of SE in Surabaya city. A Non-linear Static Procedure (NSP) or pushover analysis and Non-linear Dynamic Procedure (NDP) or time history analysis are employed to evaluate the performance of the structure. The evaluation is conducted at three earthquake levels which are nominal earthquake that is used in second model, earthquake corresponding to EDRS level, and maximum considered earthquake (MCE_R) specified by the code (50% higher than EDRS level). The building performances satisfy the drift criteria in accordance with FEMA 273. However, the partial side sway mechanism was not achieved at NDP analysis at maximum seismic load, MCE_R.

1. Introduction

Due to major seismic event, structures may develop a collapse mechanism, either beam side sway mechanism or soft storey mechanism (Figure 1). Because of its instability, the soft storey mechanism must be avoided, and to ensure the beam side sway mechanism, strong column weak beam principle must be employed in the design. This design concept is widely accepted and commonly known as the Capacity Design (CD) method. Since the columns should be designed stronger than maximum probable forces that may be developed in beams, the columns can only be designed after the beams, which is inefficient.
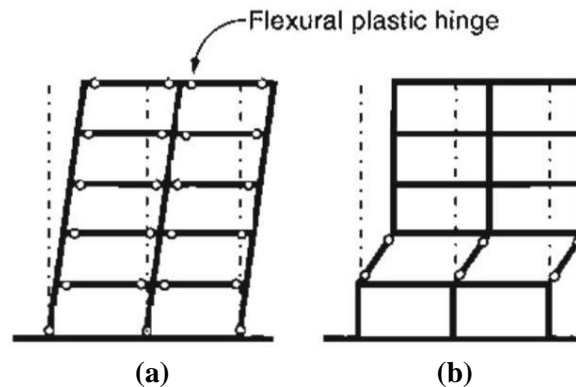
Figure 1. Collapse mechanism [1], (a) Beam side sway mechanism (b) Soft storey mechanism.

According to Paulay, the beam capacity of a gravity dominant building, especially low-rise building with long span beam, is determined by gravity load rather than seimic load [2]. Therefore, the design for column will be excessive to ensure strong column weak beam principle. Other collapse mechanism was proposed namely the partial side sway mechanism (Figure 2) where some exterior columns are designed to remain elastic and interior columns are allowed to be in plastic condition thus preventing the soft storey mechanism. This stable partial side sway mechanism was adopted in a design method proposed by Muljati and Lumantarna [3]. The design method was introduced as the Partial Capacity Design (PCD) method.
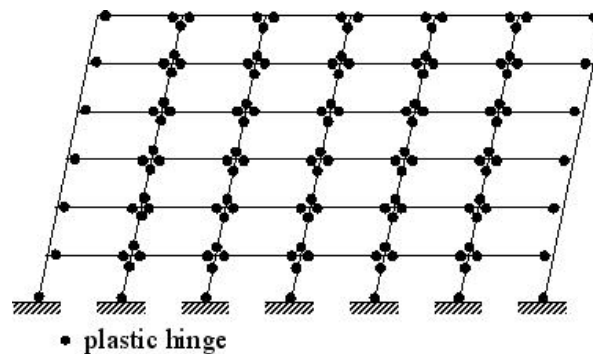

Figure 2. Partial side sway mechanism [3].

2. Partial Capacity Design (PCD)
In designing exterior columns, Muljati & Lumantarna [3][4][5] have been developing the PCD method by using a magnification factor to amplify the earthquake induced internal forces. The design procedure of PCD is illustrated in Figure 3. The PCD method has been proved to be more efficient than the CD method in term of design effort. However, in some cases the observed mechanisms were not as expected as plastic damages still occurred in some exterior columns. Inaccurate internal forces of the structure during non-linear stage might be the cause. The magnification factor used to predict the forces is a single constant value. It is logical that this may introduce inaccuracy since the distribution of forces is very dependent on the element stiffnesses.
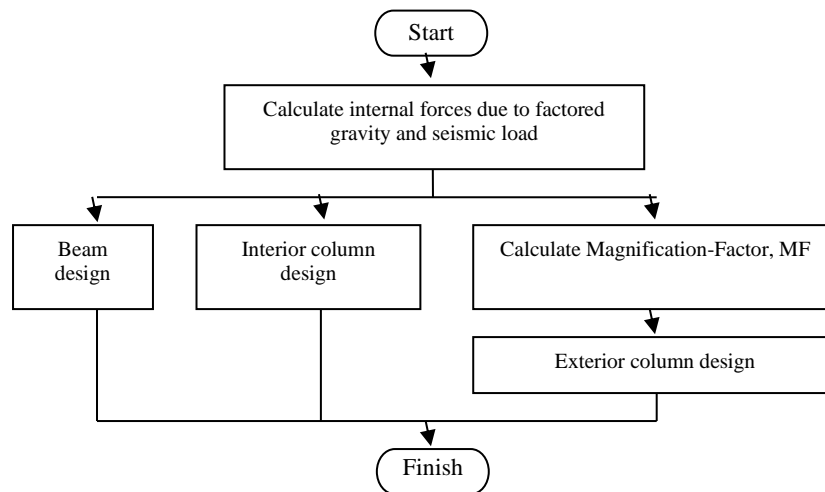
Figure 3. Flowchart of PCD method [3].

In this research, a different approach to achieve the partial side sway mechanism is proposed. A second structural model with some stiffness modifications to stimulate expected plastic damaged is used to obtained the exterior columns design forces, rather than using a magnification factor as in the original PCD method. This method, the Modified Partial Capacity Design (M-PCD) is expected to perform more effectively in achieving the partial side sway mechanism, since distribution of internal forces at non-linear stage are analysed directly in the second model

3. Modified Partial Capacity Design (M-PCD)

There are two structural models which are used in this method. The first model used for designing beams and columns where plastic damages are allowed. The strong column weak beam concept was not employed as the columns may experience axial-flexural plastic damages, however shear damages are still prevented in both beams and columns (designed by using actual flexural capacities of corresponding elements). Assuming that the structure may still develop good ductility, the first model is designed to withstand seismic load with seismic reduction factor, (R) of 8. The second model is modified from the first model by reducing stiffnesses of the elements in which plastic damages are expected to occur. The moment of inertia of the element was modified to 0.2% of its initial value to model the plastic damages. The second model is then designed to withstand seismic load with seismic reduction factor (R) of 1.6 (no ductility is expected from columns that remain undamaged). The two models are illustrated in Figure 4 and the flowchart of M-PCD method is illustrated in Figure 5.
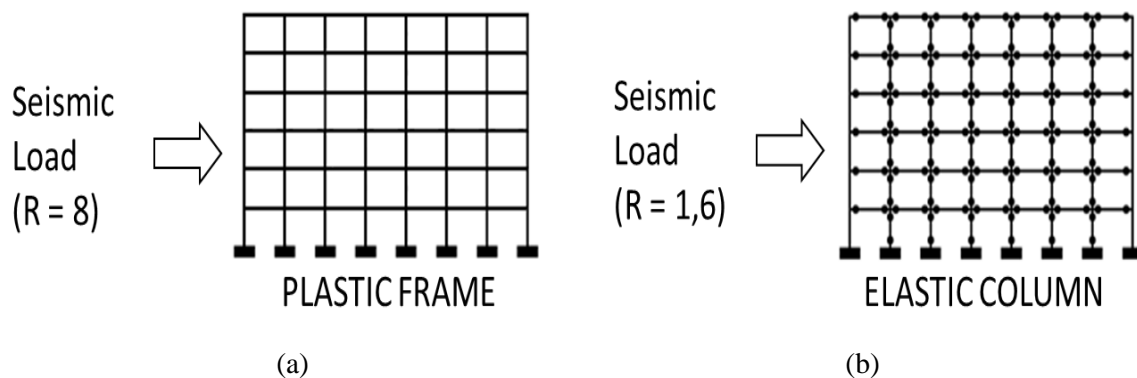

(a)　　　　　　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 4. Structural model for designing: (a) plastic frames (b) elastic columns.
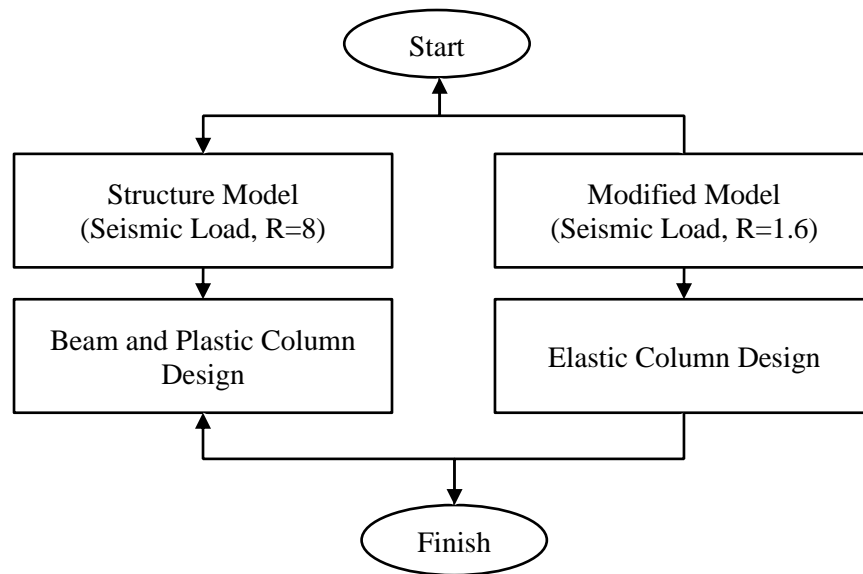
Figure 5. Flowchart of M-PCD method.

3.1. Considered buildings

Six and ten storey buildings with uniform storey height of 3.50 m (Figure 6) were adopted from Tjahjono and Dwiyanti [6] with slight modification of element dimensions are used in this research. The modification was meant to minimize the design overstrength from plastic frames and to provide better strength of elastic columns. The modified element dimensions are shown in Table 1 and the gravity loads are shown in Table 2.
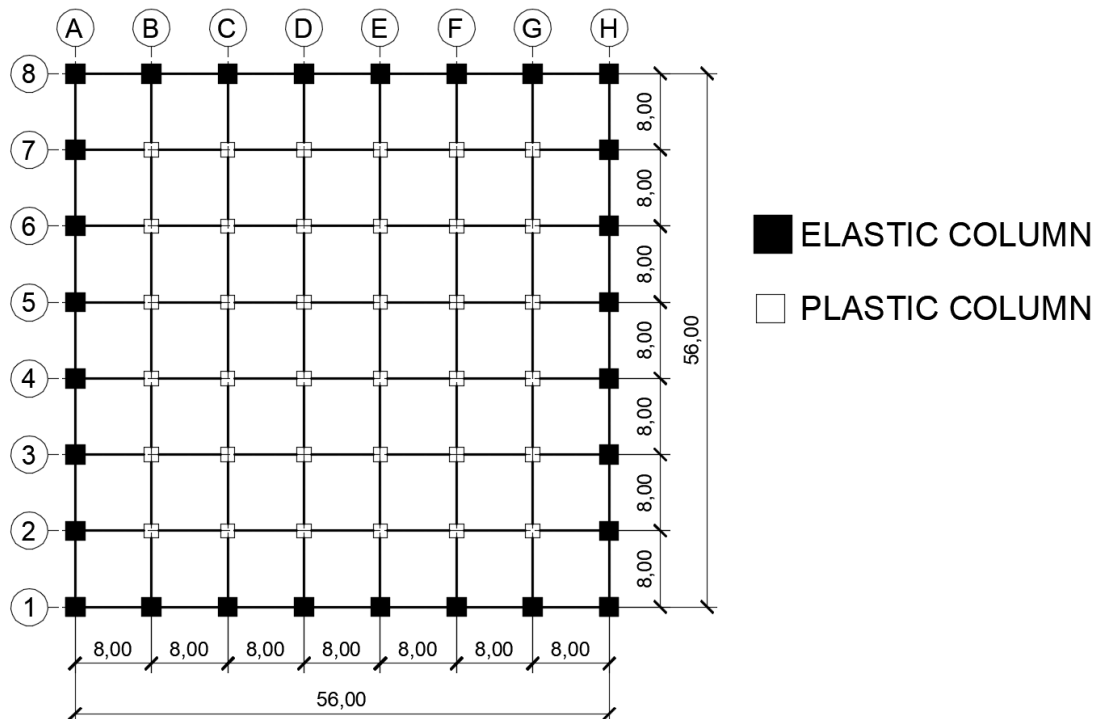

Figure 6. Layout plan of the 6 and 10 storey buildings.

Table 1. Properties and dimensions of the elements.

Storey	6 Storey		10 Storey	
	Elastic Column	Plastic Column	Elastic Column	Plastic Column
9-10	-	-	600×600	350×350
7-8	-	-	750×750	425×425
5-6	600×600	350×350	900×900	500×500
3-4	750×750	425×425	1000×1000	575×575
1-2	900×900	500×500	1100×1100	650×650

Beams : 300 × 700 mm

Slab thickness : 120 mm

Concrete compressive strength, $fc' = 30$ MPa

Yield strength of longitudinal reinforcement, $fy = 420$ MPa

Yield strength of transverse reinforcement, $fyt = 420$ MPa

Table 2. Gravity loads.

Storey	6 Storey			10 Storey		
	Dead Load (kN/m²)	Wall (kN/m)	Live Load (kN/m²)	Dead Load (kN/m²)	Wall (kN/m)	Live Load (kN/m²)
Storey 10				1.7	-	1
Storey 9				1.7	4.2	2.4
Storey 8				1.7	4.2	2.4
Storey 7				1.7	4.2	2.4
Storey 6	1.7	-	1	1.7	4.2	2.4
Storey 5	1.7	4.2	2.4	1.7	4.2	2.4
Storey 4	1.7	4.2	2.4	1.7	4.2	2.4
Storey 3	1.7	4.2	2.4	1.7	4.2	2.4
Storey 2	1.7	4.2	2.4	1.7	4.2	2.4
Storey 1	1.7	4.2	2.4	1.7	4.2	2.4

3.2. Modification of structure model (second model)

The stiffness modifications are applied in plastic frames at potential hinge locations along their plastic hinge lengths (Figure 7). It should be noted that once the design is completed, actual non-linear hinge properties are assigned to the first model for structural performance evaluation. The modification factor is taken from the ratio of plastic stiffness slope to elastic stiffness slope from typical moment-curvature curve of the reinforced concrete elements. A typical moment-curvature generated by using CUMBIA [7] is shown in Figure 8. The calculated modification factor value is about 0.002.
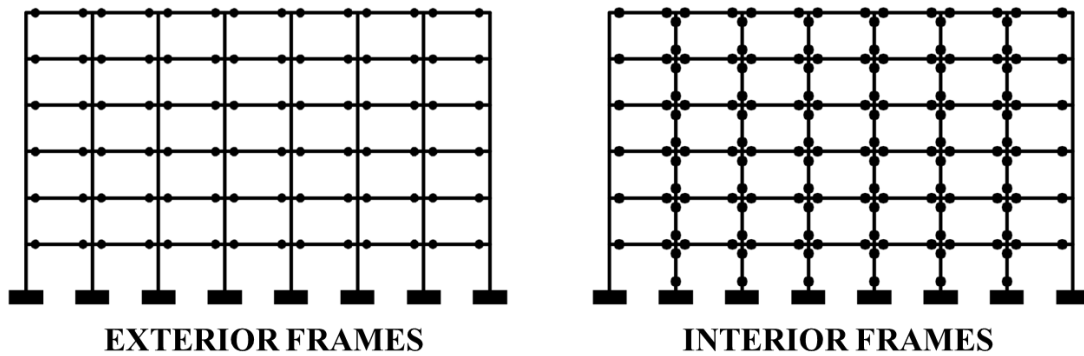
EXTERIOR FRAMES   **INTERIOR FRAMES**

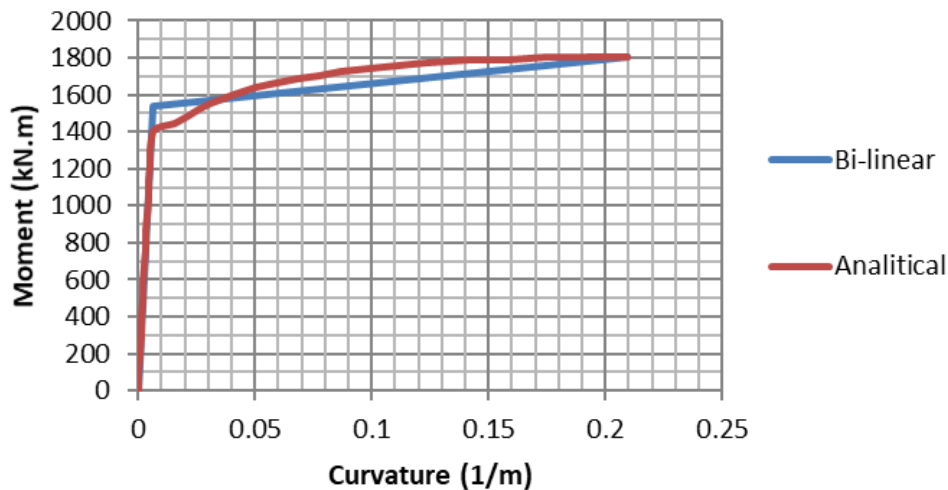**Figure 7.** Plastic hinges on modified structure model.

Figure 8. Typical moment-curvature relationship.

4. Results and discussions

The performance of the structures was analyzed by using Nonlinear Static Procedure (NSP) and Nonlinear Dynamic Procedure (NDP). NSP was executed by applying lateral load pattern in accordance to its first mode with a drift target of 4%. While NDP was analyzed by using spectrum consistant ground acceleration generated from El Centro 1940 in accordance to Indonesian Seismic Code [8].

4.1. Drift

The maximum drift ratio of each storey obtained from NSP and NDP procedures are shown in Figures 9a and 9b, respectively at EDRS and MCE_R seismic levels for the 6 storey building. Figure 10 shows drift ratios of the 10 storey building. With allowable drifts according to FEMA 273 [9], which are 2% and 4% for EDRS and MCE_R levels respectively, it can be observed that the buildings satisfied the drift requirements.
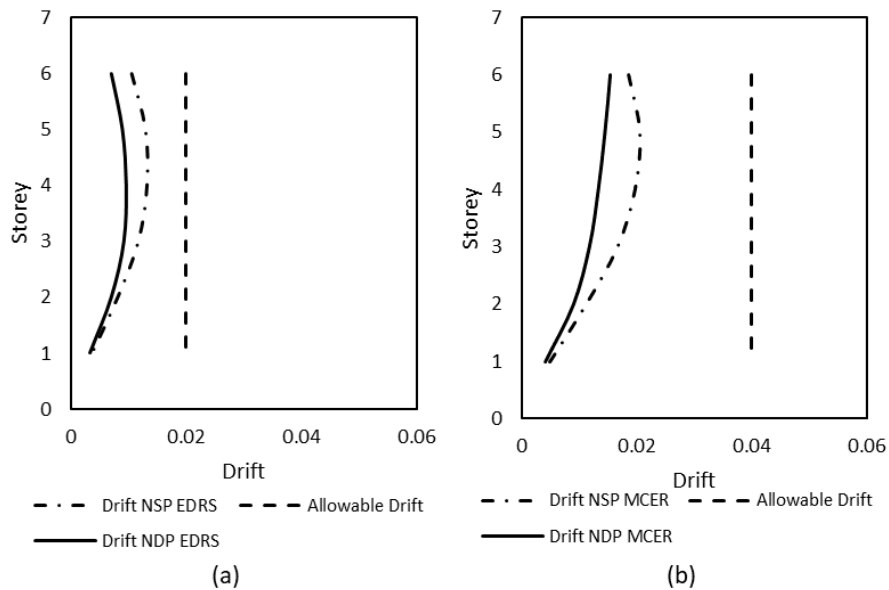
Figure 9. Drift of 6-storey building (a) EDRS level (b) MCE$_R$, level.
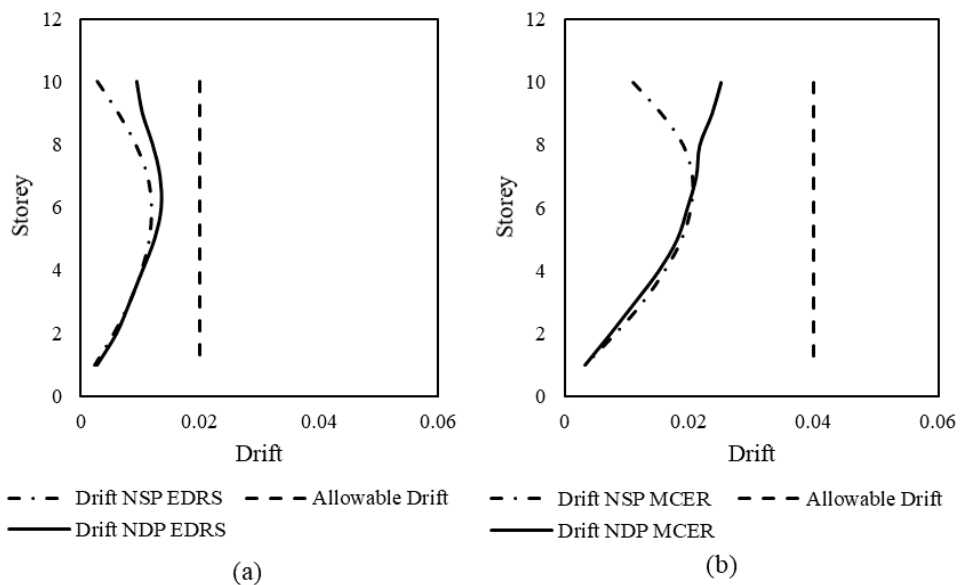

Figure 10. Drift of 10-storey building (a) EDRS level (b) MCE$_R$, level.

4.2. Partial sidesway mechanism

From the occurrence of plastic damages, the failure mechanism of the buildings can be observed. Partial side sway mechanisms of the structures are observed at NSP procedure, and at the end of NDP procedure. Plastic hinges are presented at axes 1 and 4 for typical exterior and interior frames, respectively at EDRS and MCE$_R$ level. These plastic hinges are shown in Tables 3 and 4 for 6-and 10-storey buildings, respectively.

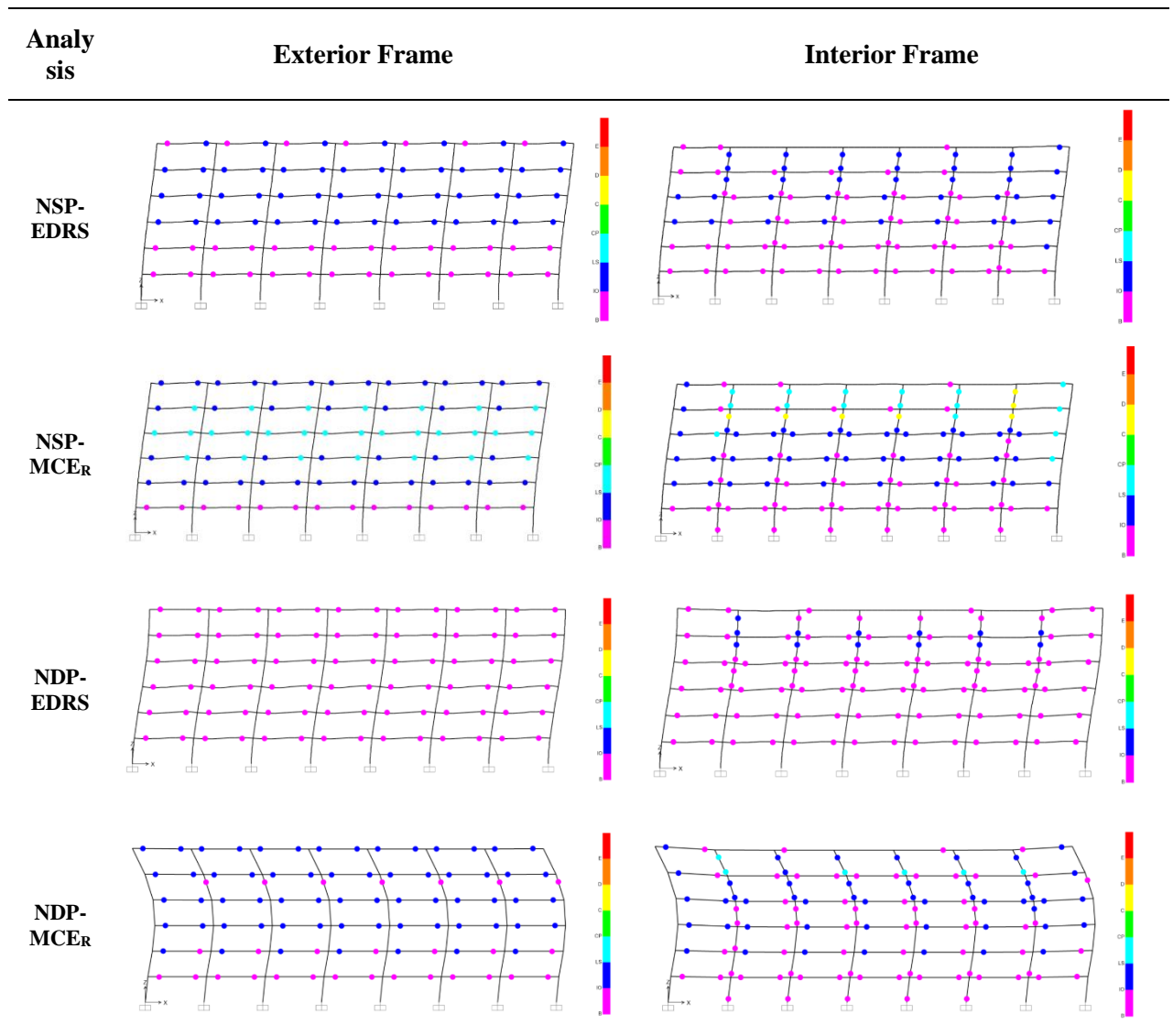**Table 3.** Plastic hinges on 6-storey building.

Analysis	Exterior Frame	Interior Frame
NSP-EDRS		
NSP-MCE$_R$		
NDP-EDRS		
NDP-MCE$_R$		

Table 4. Plastic hinge on 10-storeys building.

Analysis	Exterior frame	Interior frame
NSP-EDRS		
NSP-MCE$_R$		
NDP-EDRS		
NDP-MCE$_R$		
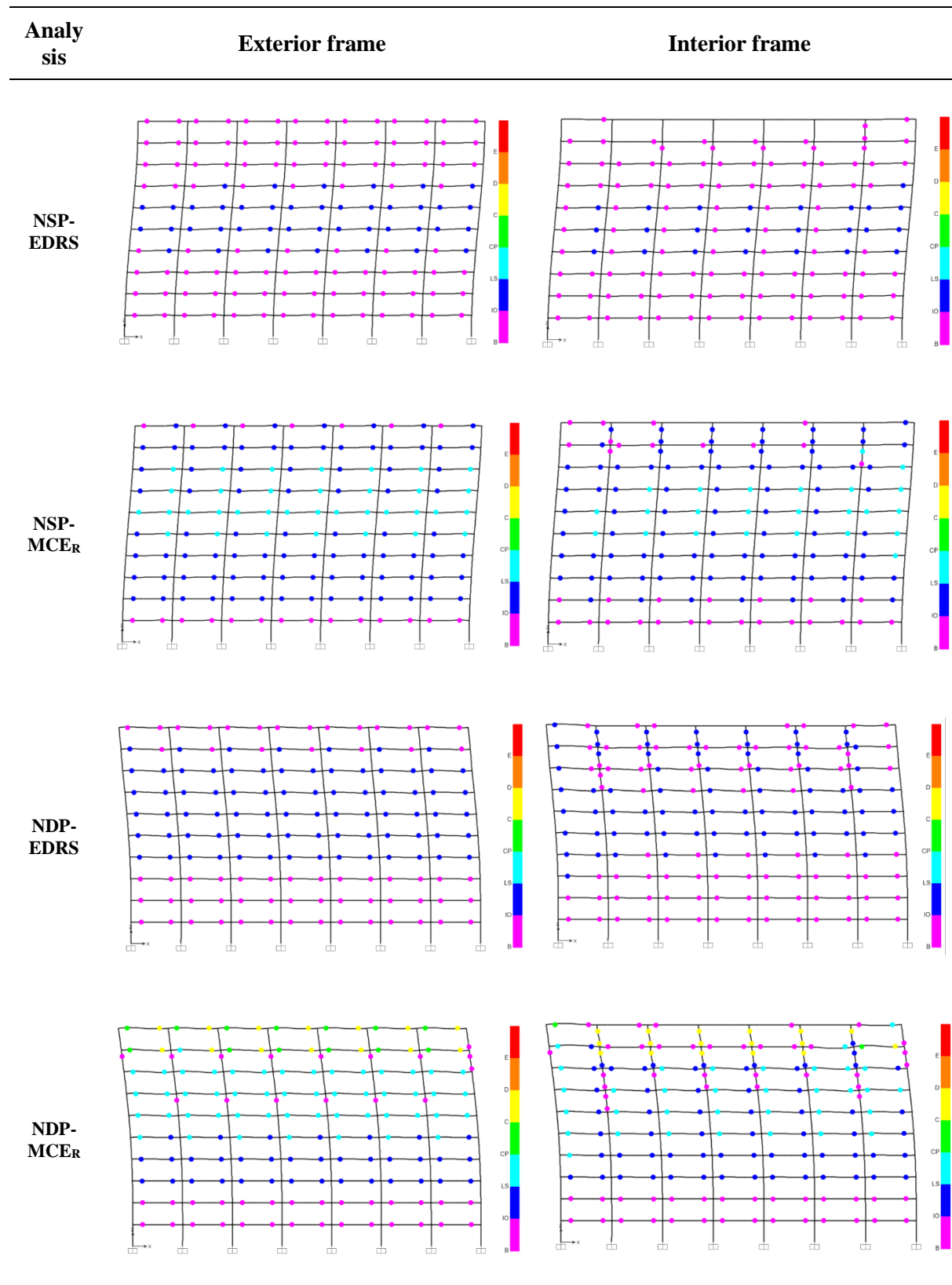
5. Concluding remarks

In general, structures designed by using the M-PCD can undergo target earthquake with stable partial side sway mechanism. However, an exception is still observed that unexpected plastic hinges occurred at upper-middle of the building in NDP procedure at MCE_R seismic level. But it should be noted that MCE_R level is much higher than that of the nominal earthquake for design. One alternative to overcome this is by simply modify the seismic reduction factor in the design process. The M-PCD methods has given an alternative approach to the PCD method, nevertheless further study and development are still needed for this proposed design method.

Acknowledgements

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