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Application of Modified-Partial Capacity Design Method on 6- and 15-story Square Buildings with Variation in number of Elastic Columns

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Abstract: Modified-Partial Capacity Design (M-PCD) is proposed as one alternative of structural design methods. In M-PCD, the partial side sway mechanism where beams and some columns may develop plastic hinges. This method uses two structural models during the design process. The models are used to simulate undamaged and damaged structures when subjected to design earthquake (R=8.0) and larger target earthquake (R=1.6) respectively. In this study, 6- and 15-story square buildings with 30% and 50% elastic column are designed using M-PCD. Performances of the buildings are investigated by using non-linear time history analysis. Results show that the buildings' performances are still unsatisfactory, especially for the 15-story buildings. However, it should be noted that the levels of earthquakes used for the analysis were larger than that used for the design. A more accurate prediction of the required strength should be developed further to improve M-PCD.

Keywords: Modified-partial capacity design; partial side sway mechanism; structural analysis; elastic column; plastic column.

Introduction

Capacity design (CD) is the most widely used method for earthquake-resistant structure design, CD allows side sway failure mechanism. This safe failure mechanism is ensured by designing the columns to be stronger than the beams (strong column weak beam). Alternatively, Partial capacity design (PCD) offers other earthquake-resistant structure design method. In PCD, partial side sway mechanism, which was introduced by Paulay and Priestley [1], is adopted. In this mechanism, some columns are allowed to experience plastic hinges, which means the capacity of the columns is not necessarily stronger than the beams' capacity. These columns are called plastic columns, whereas the remaining columns are called elastic columns.

In order to predict the required strength of the elastic columns, PCD has used a magnification factor to scale up the internal forces of these columns. Early studies on this approach [2-6] showed some inadequate performances that some elastic columns still experienced plastic damages. Pudjisuryadi, et. al. [6] mentioned that the ratio of actual to required flexural reinforcement of beams should be kept as low as possible in order to avoid damages to the elastic columns since these columns are designed without considering the beams' capacity.

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Tanaya et al. [7] has proposed Modified-Partial Capacity Design (M-PCD) which suggested a different approach in predicting the required strength of elastic columns. M-PCD uses two structural models in the design process. The first model is used to design beams and plastic columns, while the second model is used to design elastic columns. The seismic modification factors (R) used were 8.0 and 1.6 for earthquake design levels of the first (DER_{80}) and second (DER_{16}) models, respectively. In the second model, there are flexural stiffness modifications for beams and plastic columns to simulate plastic damages. In this study, 6- and 10- story buildings are designed by using M-PCD method and analyzed by using non-linear time history analysis. Two levels of earthquakes which corresponded to the elastic design earthquake (EDRS) and the maximum considered earthquake (MCE_R) were used in the analysis. Figure 1 shows the response spectra of four-level earthquakes which were used for design and analysis. Results of this study showed that plastic damages in elastic columns were observed at maximum considered earthquake (MCE_R) level, which is much larger than the design earthquake (see Figure 1).

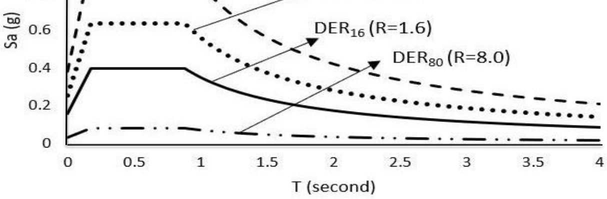


Figure 1. Comparison of Earthquake Levels used for Design and Analysis

The M-PCD method has been further developed by Pudjisuryadi et al. [8]. In this study, the second model is only subjected to seismic load equal to the difference between earthquakes with seismic reduction factors of 1.6 and 8.0. The required strength of elastic columns is obtained by the superposition of internal forces from the first and second models. The effect of gravity load should only be accounted once in this superposition. In this study, 6- and 10- story buildings with rectangular plans were designed and analyzed. Number of elastic columns are varied. The results showed that no damages were found in elastic columns.

The Proposed Development of M-PCD

Previously [7,8], structural elements were divided into three parts in order to locally modify flexural stiffness at potential plastic hinge locations, but this is considered time-consuming in preparing the second model. In this paper, a slight simplification of the M-PCD method is proposed. The flexural stiffness modification in the second model is applied in the full length of the structural elements. The flexural stiffness modifications were assumed arbitrarily as 0.2 and 0.35 for beams and plastic columns, respectively. In addition, elastic columns were also modified at the bottom stories similar to plastic columns, since plastic damages were allowed at the base. The models which were used for design in this study are presented in Figure 2.

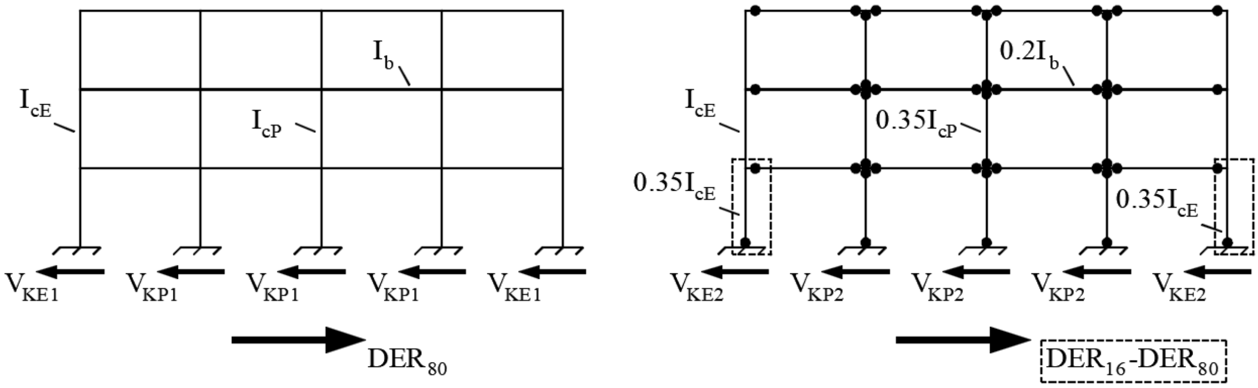
Considered Buildings

In this study, 6- and 15-story concrete buildings were designed with the proposed approach. The number of elastic columns were 30% and 50% of the total columns. There were two placement variations of elastic columns. In the first configuration, all elastic columns were located in the perimeter of the building (Type A), in the second, 50% of the elastic columns were moved to the interior of the buildings (Type B). In total, 8 buildings were investigated, namely 6A-30%, 6B-30%, 6A-50%, 6B-50%, 15A-30%, 15B-30%, 15A-50%, and 15B-50%, see Figure 3 for plan of the buildings. The typical elevation view of the buildings' frames can be seen in Figure 4.

The live load used was based on SNI 1727:2020 [9] while the dead loads were the self-weight and superimposed load (ceiling, ducting, tiles and plaster). The dimensions of the beams were 300x500 mm^2 and 300x600 mm^2 for the 6-story and 15-story buildings, respectively. The dimensions of the columns are presented on Table 1. The beams and columns are designed according to SNI 03-2847-2019 [10], without considering the strong column weak beam concept in the column design. The resulting reinforcement ratio is shown in Table 2. It should be noted that the sum of top and bottom reinforcement area was used to calculate the beam reinforcement ratio in Table 2. It can be seen that on average, 6-story buildings with all elastic columns located on the building perimeter (Type A) required less reinforcements, but the opposite was true for the 15-story buildings.

Table 1. Plastic Column and Elastic Column Dimension

Story	6A & 6B		15A & 15B	
	Plastic Column	Elastic Column	Plastic Column	Elastic Column
1	450x450	900x900	800x800	1100x1100
2	450x450	800x800	800x800	950x950
3	400x400	700x700	750x750	850x850
4	400x400	600x600	700x700	850x850
5	350x350	550x550	650x650	800x800
6	325x325	550x550	650x650	800x800
7			600x600	800x800
8			550x550	800x800
9			500x500	800x800
10			500x500	800x800
11			450x450	750x750
12			450x450	750x750
13			400x400	700x700
14			400x400	700x700
15			350x350	700x700



*KE = Elastic Column, KP = Plastic Column
*V_{KE1} = Base Shear of Elastic Column in Model 1
*V_{KP1} = Base Shear of Plastic Column in Model 1
*V_{KE2} = Base Shear of Elastic Column in Model 2
*V_{KP2} = Base Shear of Plastic Column in Model 2

Figure 2. Seismic Loads and Flexural Stiffness Used in the Design: (a) Model 1; (b) Model 2

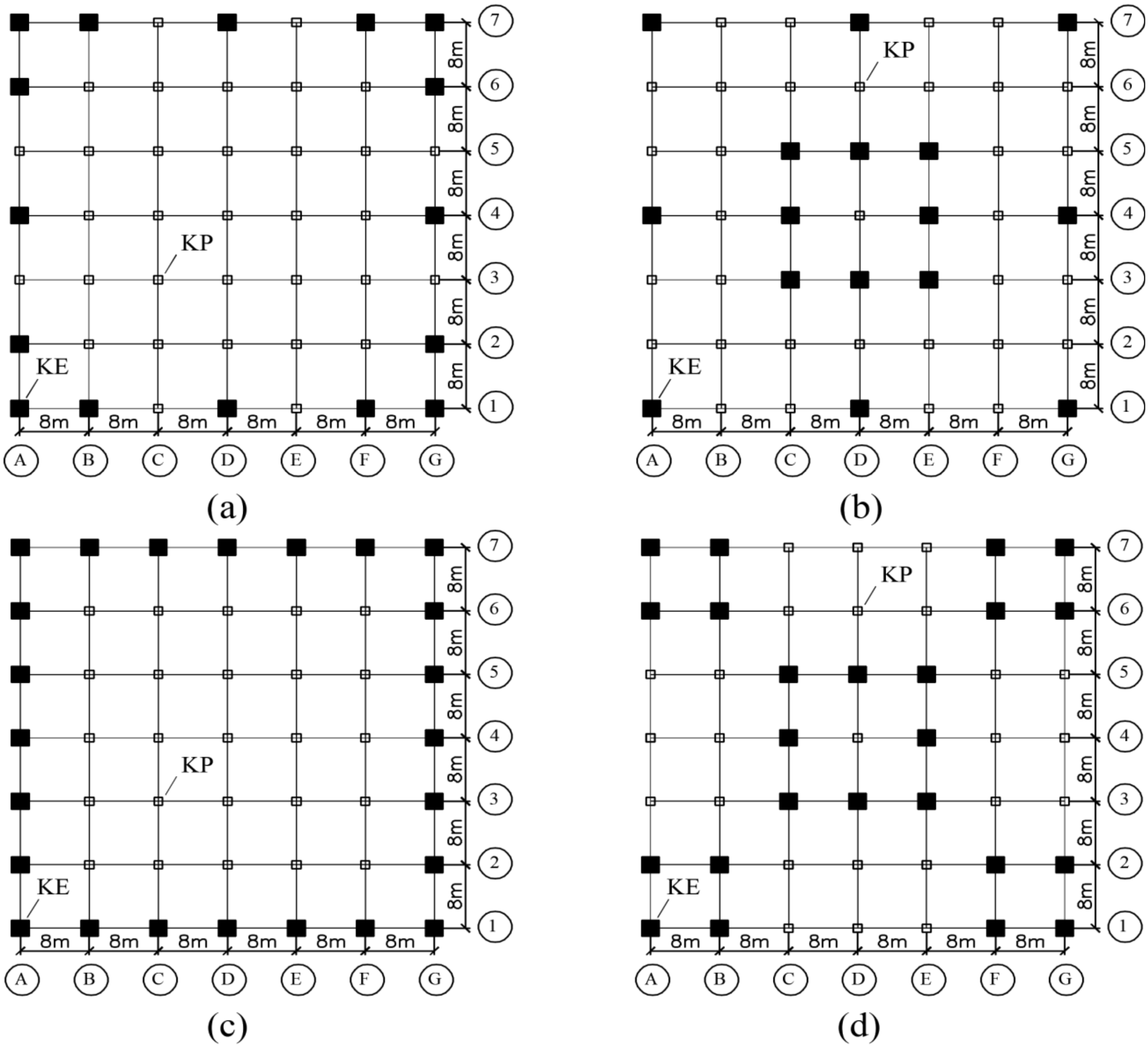


Figure 3. Plan View of the Buildings: (a) 6A-30% & 15A-30%; (b) 6B-30% & 15B-30%; (c) 6A-50% & 15A-50%; and (d) 6B-50% & 15B-50%

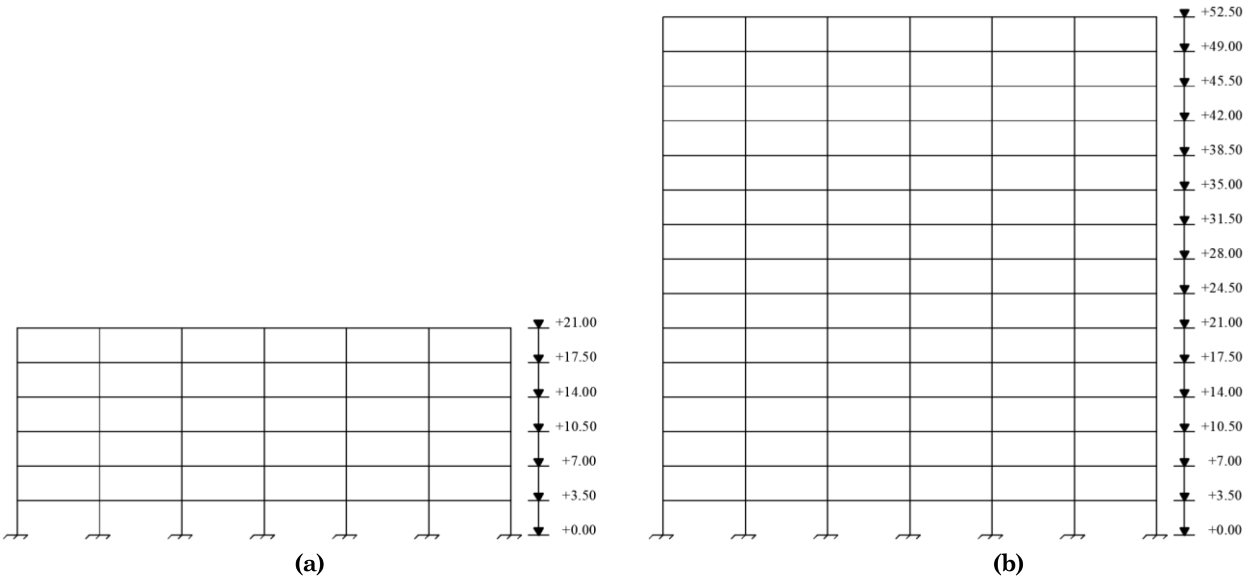


Figure 4. Elevation Views: (a) 6-story Building; and (b) 15-story Building

Table 2. Reinforcement Ratio

Building Type	Exterior Beams	Interior Beams	Plastic Columns	Elastic Columns	Average
6A-30%	2.05%	3.00%	3.80%	3.08%	2.98%
6B-30%	2.05%	2.95%	4.05%	3.80%	3.21%
6A-50%	1.98%	3.04%	2.56%	3.01%	2.65%
6B-50%	1.95%	2.71%	3.79%	3.40%	2.96%
15A-30%	1.82%	2.55%	2.35%	1.94%	2.16%
15B-30%	1.90%	2.18%	2.10%	1.98%	2.04%
15A-50%	1.80%	2.56%	2.26%	2.44%	2.27%
15B-50%	1.82%	2.38%	2.05%	2.30%	2.14%

Performance of the Buildings

The structures were analyzed by using non-linear dynamic procedure (NDP) or non-linear time history analysis (NLTHA). The ground motion used was spectrum consistent acceleration generated from the Imperial Valley 1940 earthquake recorded in El-Centro station [11]. The spectrum used to modify the ground motion was Surabaya response spectrum [12,13] with site class E soil. There were two levels of earthquake used for analysis, which corresponded to

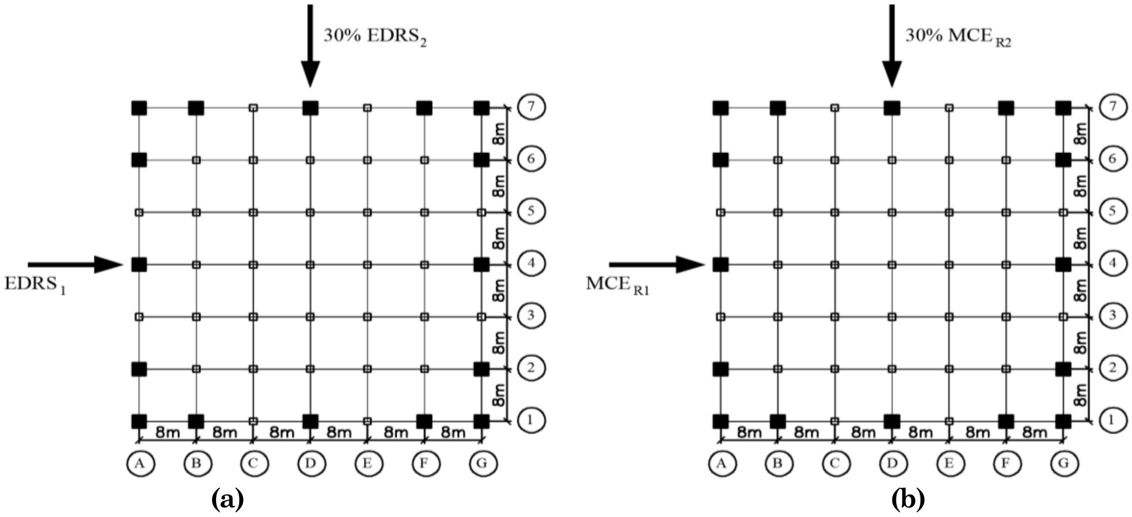


Figure 5. Applied Seismic Load for Non-linear Dynamic Procedure (NDP) Analysis: (a) EDRS Level; and (b) MCE_R Level

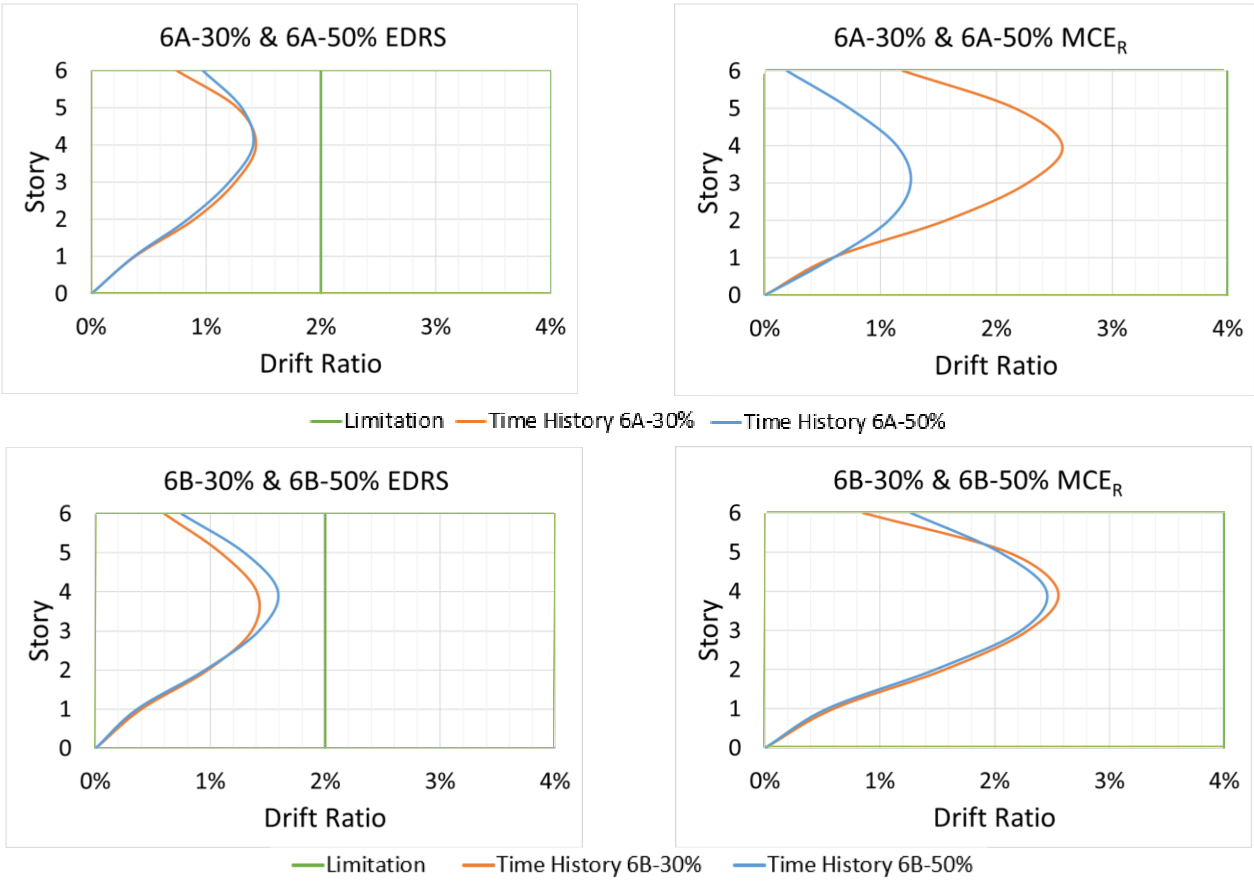


Figure 6. Drift Ratio for 6A and 6B buildings

the elastic design response spectrum (EDRS) and maximum considered earthquake (MCE_R). It should be noted that these earthquake levels are larger than the used design earthquake (see Figure 1). The ground motions were applied in two orthogonal directions, with only 30% intensity for the minor direction as presented in Figure 5. The resulting drift ratios, failure mechanisms and plastic damage levels were investigated.

The drift ratios of 6-story and 15-story buildings are presented in Figures 6 and 7. It can be seen that almost all buildings meet the drift limitations according to FEMA 356, 2000 [14] which are 2% and 4% for elastic design earthquake (EDRS) and maximum considered earthquake (MCE_R), respectively. Only building 15A-50% exceeded the drift limitation at EDRS level. The detail values of the drift ratios are listed in Table 3. Table 4 lists this building as unsafe (US) in the drift criteria.

The failure mechanisms of the buildings were found unsatisfactory, that some elastic columns still suffered plastic damages. Some examples of such damages are presented in Figures 8 to 11. The color of the plastic hinges represents the damage level, as shown in Table 4. All buildings that experienced damages exceeding partial side sway mechanism are marked unsafe (US) and listed in Table 5.

Table 3. Maximum Drift Ratio

Type	Time History EDRS	Time History MCE_R
6A-30%	1.44%	2.57%
6B-30%	1.41%	2.55%
6A-50%	1.41%	1.26%
6B-50%	1.59%	2.45%
15A-30%	1.88%	2.28%
15B-30%	2.00%	2.50%
15A-50%	2.25%*	2.81%
15B-50%	1.88%	2.12%

* (highlighted): Drift value exceeding the limitation

Table 4. Plastic Hinge Color and State

	Plastic Hinge State
B	B
IO	*Immediate Occupancy*
LS	*Life Safety*
CP	*Collapse Prevention*
C	*Collapse*
D	D
E	E

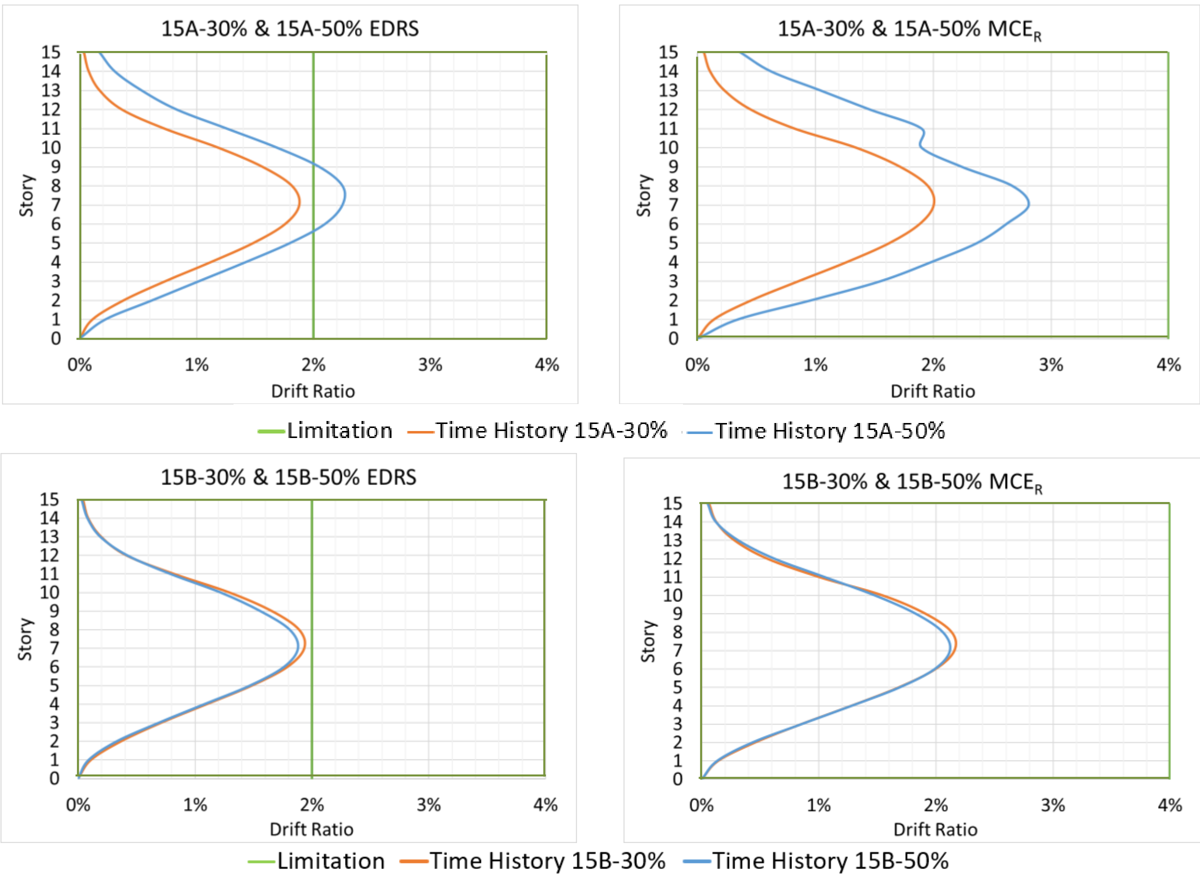


Figure 7. Drift Ratio for 15A and 15B Buildings

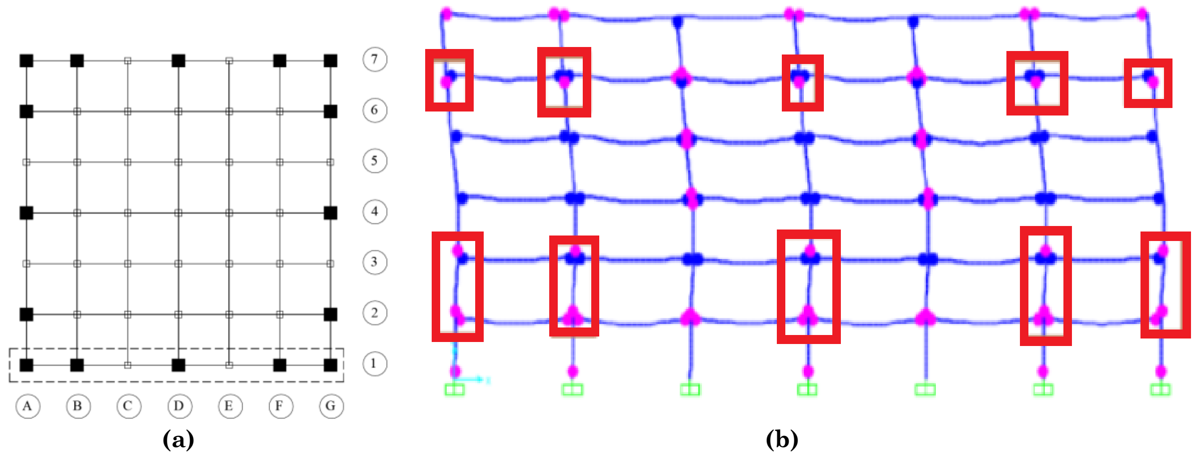


Figure 8. Plastic Damages of Building 6A-30% due to MCE$_R$ at Frame 1: (a) Plan View; (b) Elevation View

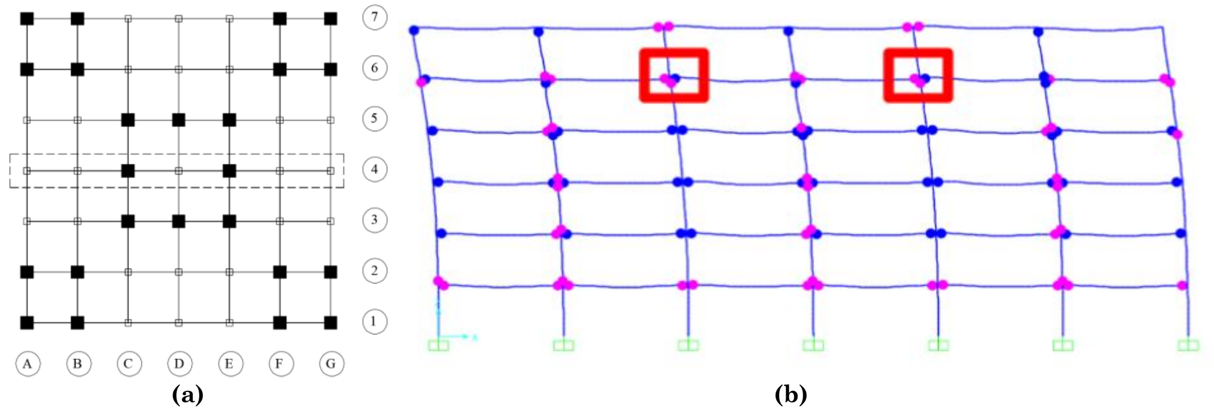


Figure 9. Plastic Damages of Building 6B-50% due to MCE$_R$ at Frame 4: (a) Plan View; (b) Elevation View

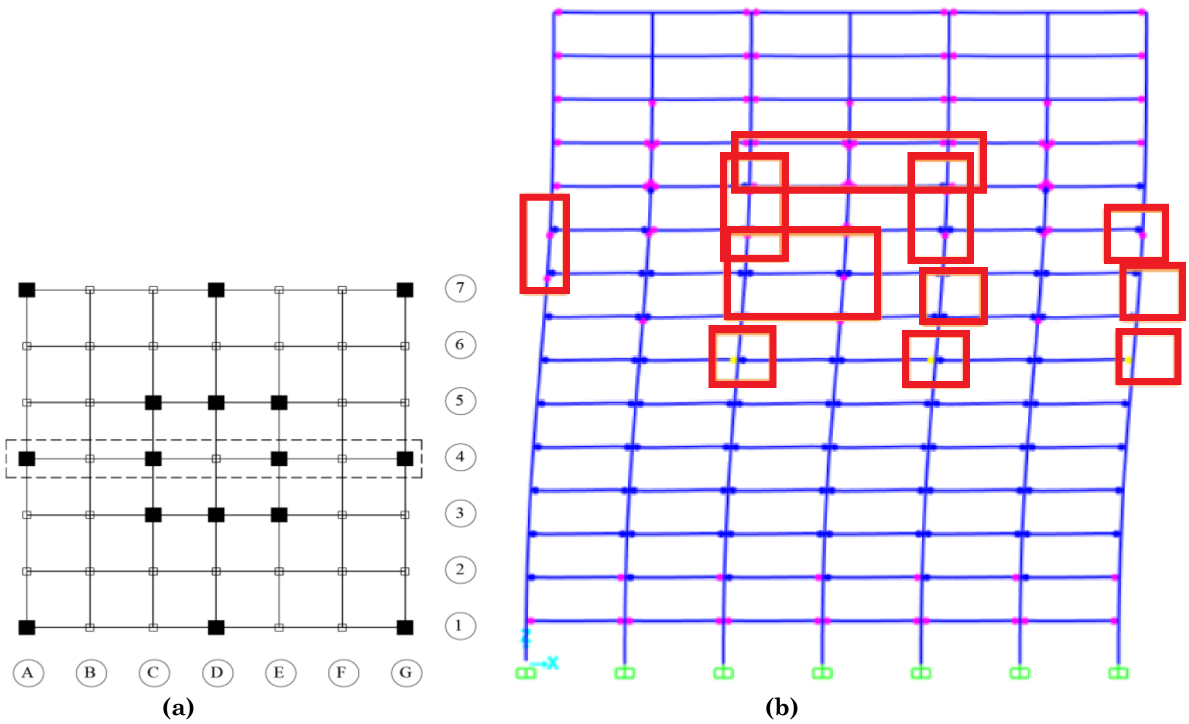


Figure 10. Plastic Damages of Building 15B-30% due to MCE$_R$ at Frame 4: (a) Plan View; (b) Elevation View

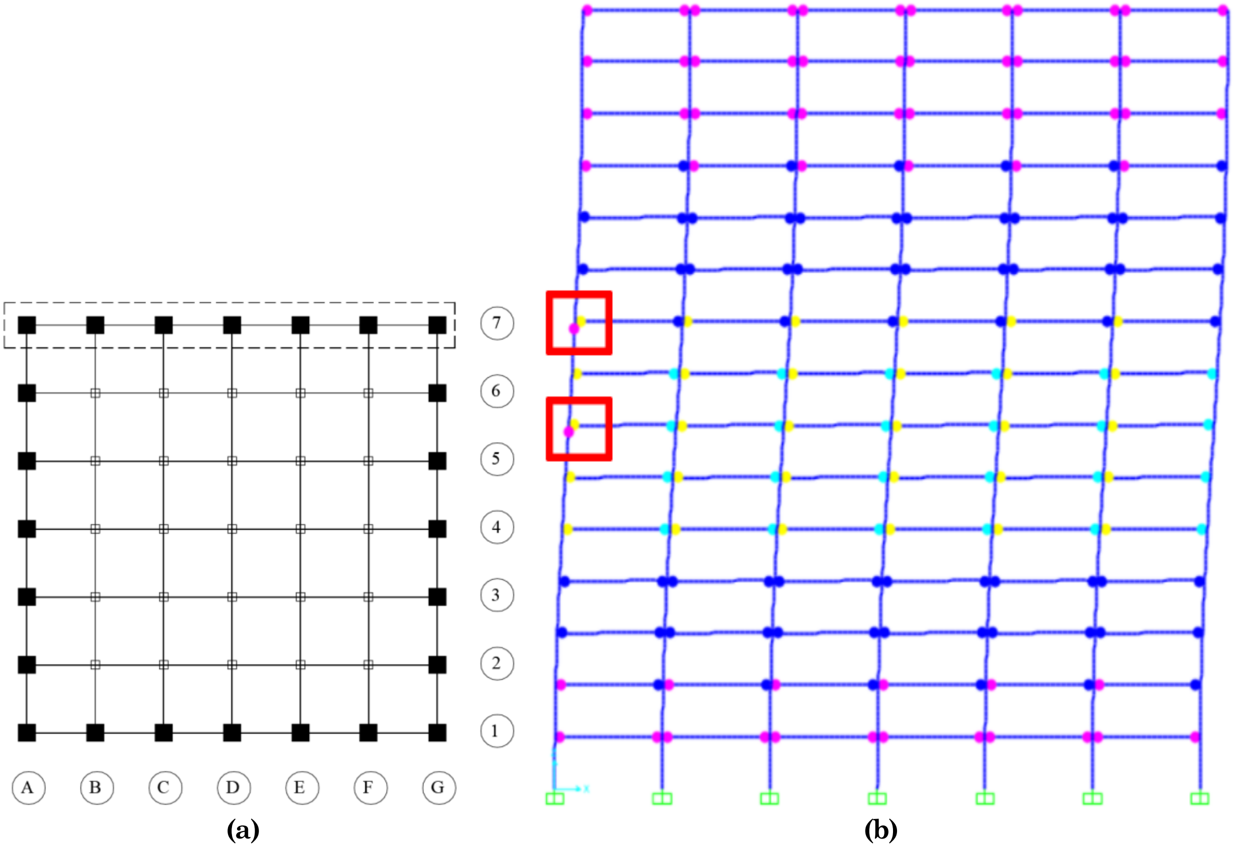


Figure 11. Plastic Damages of Building 15A-50% due to MCE$_R$ at Frame 7: (a) Plan View; (b) Elevation View

Table 5. Summary of Analysis Results for 6 and 15-Story Buildings

Type	Time History EDRS			Time History MCE$_R$		
	Mechanism	Drift	Hinge Level	Mechanism	Drift	Hinge Level
6A-30%	S	S	US	US	S	S
6B-30%	US	S	US	US	S	S
6A-50%	S	S	US	S	S	S
6B-50%	S	S	US	US	S	S
15A-30%	US	S	US	US	S	US
15B-30%	US	S	S	US	S	S
15A-50%	S	US	US	US	S	US
15B-50%	S	S	S	US	S	US

*S: Safe *US: Unsafe
*US: Hinges occurs on elastic columns
*US: Drift exceeds the allowable drift according to FEMA 356 [14]
*US: Hinge level > Life Safety (exceeds design earthquake limits)
*US: Hinge level > Collapse Prevention (exceeds maximum earthquake limits)

The severity of plastic hinge damages was reviewed with the FEMA 356 limitation [14]. The maximum damage levels are expected as life safety and collapse prevention for EDRS and MCE$_R$ earthquake levels. The summary of this maximum plastic damages is listed in Table 5, and buildings which did not meet the criteria are marked as unsafe (US).

Conclusion

The proposed Modified Partial Capacity Design method has been presented. Some building configurations were chosen to test the reliability of the method. From the results of the analysis, some concluding remarks can be listed as follows:

1. Most of the considered buildings meet the allowable drift ratio set by FEMA 356 [14], which are less than 2% and 4% for elastic design earthquake (EDRS) and maximum considered earthquake (MCE_R) levels, respectively. The only building that did not meet the criteria is building 15A-50%.
2. The worst expected failure mechanism, which is the partial side sway mechanism, is exceeded in almost all of the considered buildings, where some elastic columns suffered plastic damages.
3. The maximum level of plastic damages set by FEMA 356 [14] was exceeded in some buildings, that damages beyond "life safety" and "collapse prevention" levels were found in the buildings due to earthquakes with EDRS, and MCER levels, respectively.
4. Performance of the proposed Modified-Partial Capacity Design method is still unsatisfactory, especially for the 15-story buildings. However, it should be noted that the levels of earthquakes used for the analysis were larger than that used for the design. Nevertheless, a more accurate prediction of the required strength should be developed further.

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