SEISMIC PERFORMANCE OF STRUCTURES WITH VERTICAL GEOMETRIC IRREGULARITY DESIGNED USING PARTIAL CAPACITY DESIGN

I. MULJATI[1*†], and B. LUMANTARNA[2]

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

ABSTRACT

Partial Capacity Design (PCD) offers new alternative in seismic design of structures. Unlike Capacity Design which commonly keep all columns to remain elastic, PCD allows some columns to be elastic during severe earthquake while the other columns and beams are allowed to be plastic. In order to keep the selected columns to be elastic, they are designed based on the ultimate load multiplied by a Magnification Factor (MF). Several researches show that the method is applied well especially on the medium-rise buildings (under 10-story) which are designed as special moment resisting frame in Indonesia. The plastic hinges occur at the expected members and structures having safe collapse mechanism. Continuing the prospective results, PCD needs to be observed on irregular structures. Therefore this research is aimed to evaluate the structural performance of 6- and 10-story buildings with vertical irregularity (50% vertical set-back). The limitation of natural fundamental period as stated in SNI 03-1726-2002 clause 5.6 is not considered to avoid the use of minimum reinforcement in the design. The structural performance is evaluated using dynamic nonlinear time history analysis. Results show that PCD fails to meet the expected failure mechanism due to improper use of Magnification Factor and incorrect selection of column dimension at the vertical set-back region.

Keywords: partial capacity design, vertical irregularity, seismic performance, pushover analysis, time history analysis.

1. INTRODUCTION

Seismic design of structures usually refer to safe failure mechanism known as beam side sway mechanism. To ensure the mechanism, structures are design based on Capacity Design to maintain the condition of "strong column weak beam". Thus, columns should be designed based on the beam nominal capacity multiplied by an overstrength factor as much as 1.20 in Indonesian Concrete

* Corresponding author: E-mail: imuljati@peter.petra.ac.id

† Presenter: E-mail: imuljati@peter.petra.ac.id

Code, SNI 03-2847-2002 (BSN 2002). Consequently, the design procedure is sequential where columns could not be designed before the design of beams are completed.

Beam side sway mechanism is difficult to be achieved, the interior columns need much overstrength as prescribed by the code due to unpredictable overstrength in beams contributed by slab reinforcement and other energy dissipation during severe earthquake. Therefore, Paulay (1995) proposed another safe mechanism called partial beam side sway mechanism as shown in Figure 1. In this mechanism the interior columns are allowed to be plastic while the exterior columns are kept to remain elastic. The design procedure to fulfill the proposed mechanism is termed as Partial Capacity Design (Muljati et al. 2006).

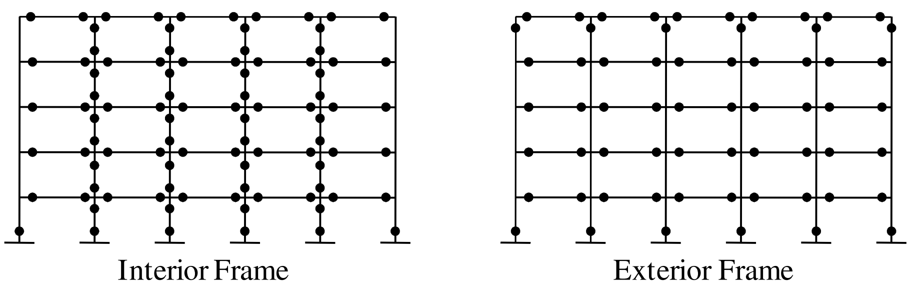

Figure 1: Partial beam side sway mechanism.

Partial Capacity Design (PCD) has been observed several times and it is applied well on regular structures (Reni and Tirtalaksa 2008; Buntoro and Weliyanto 2009; Susanto 2009). On the other hand, PCD fail to meet the expected mechanism on structures with 40% re-entrance corner (Sindynata and Wibowo 2009) due to improper selection of columns dimension at the re-entrance corner. Continuing the observation of PCD, this study is aimed to evaluate the seismic performance of the other irregular structures, i.e. vertical geometric irregularity.

2. THEORETICAL BACKGROUND

PCD assumes that during the targeted seismic load, the interior columns sustain the base shear up to the nominal seismic load multiplied by the overstrength factor, f_1 (Muljati et al. 2006). Then the excess of shear force is sustained entirely by the exterior columns according to:

$$n_{ex} \times S_{ex}^{T} = V_t^{T} - f_1 \times n_{in} \times S_{in}^{N} \tag{1}$$

where n_{ex} and n_{in} are the total number of exterior and interior columns; $S^{T}{}_{ex}$ is the shear force in the exterior column due to the target seismic load; $S^{N}{}_{in}$ is the shear force in the interior column due to the nominal seismic load; f_1 is the overstrength factor; and $V^{T}{}_{t}$ is the total base shear due to the targeted seismic load. The load distribution in PCD is shown graphically in Figure 2.

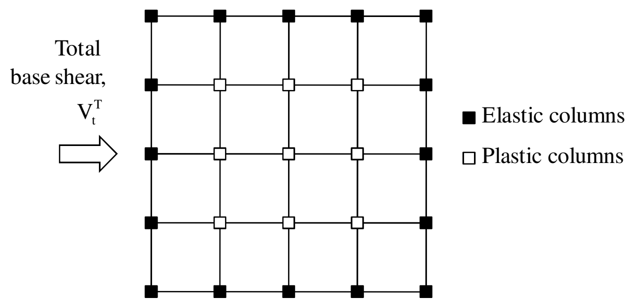

Figure 2: Load distribution in PCD

In order to keep the exterior columns to remain elastic during the targeted seismic load, they should be designed larger than the ordinary design seismic load as specified in the code. The magnification factor (MF) of the external columns' shear force is derived from:

$$MF = \frac{\left(\frac{C^T}{C^{500}}\right)\mu - 1.60\left(n_{in}R_{in}^N\right)}{\left(n_{ex}R_{ex}^N\right)} \tag{2}$$

where C^T is the spectral acceleration of the target seismic load; C^{500} is the spectral acceleration of a five hundred years return period earthquake; μ is the structural ductility; $R^N{}_{in}$ and $R^N{}_{ex}$ are the ratio of interior and exterior columns' base shear to the total base shear due to the nominal seismic load.

However, during the application of the targeted seismic load structures already in the non-linear stage, the spectral acceleration due to the five hundred years return period earthquake, C^{500} should be obtained from the non-linear response spectrum. Unfortunately, the non-linear response spectrum is not provided in the code. Therefore, it is proposed to obtain the spectral acceleration in the plastic stage, C^T, using the natural period of the structure in plastic condition predicted by the empirical correlation between the elastic and the plastic natural period ($T_{elastic}$ and $T_{plastic}$) of several structures previously observed according to:

$$T_{plastic} = 2.967T_{elastic} + 0.313 \tag{3}$$

The procedure to obtain C^T using elastic spectral acceleration is explained graphically in Figure 3.

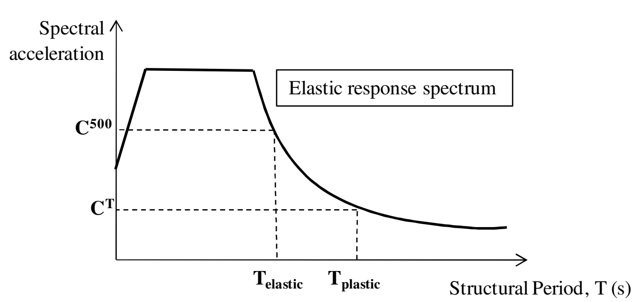

Figure 3: Spectral acceleration.

3. OBJECTIVE

The objective of this study is to observe and evaluate the seismic performance of structures with 50% vertical set-back designed using Partial Capacity Design (PCD).

4. DESIGN AND EVALUATION

Two symmetrical concrete frames with 50% vertical set-back consist of 6- and 10-story, 4-span @ 8m with equal story height of 3.50m, are used in this study (Figure 4). These buildings are assumed to be built on soft soil in zone 2 and 6 of the Indonesian seismic map (SNI 03-1726-2002) and designed using the proposed method with 500-year return period ground acceleration as the target seismic load. The limitation of natural fundamental period as stated in SNI 03-1726-2002 clause 5.6 is not considered to avoid the use of minimum reinforcement in the design. The detailed structural properties and dimension can be found in (Goenawan and Wijaya 2010; Sujanto and Lauwis 2010).

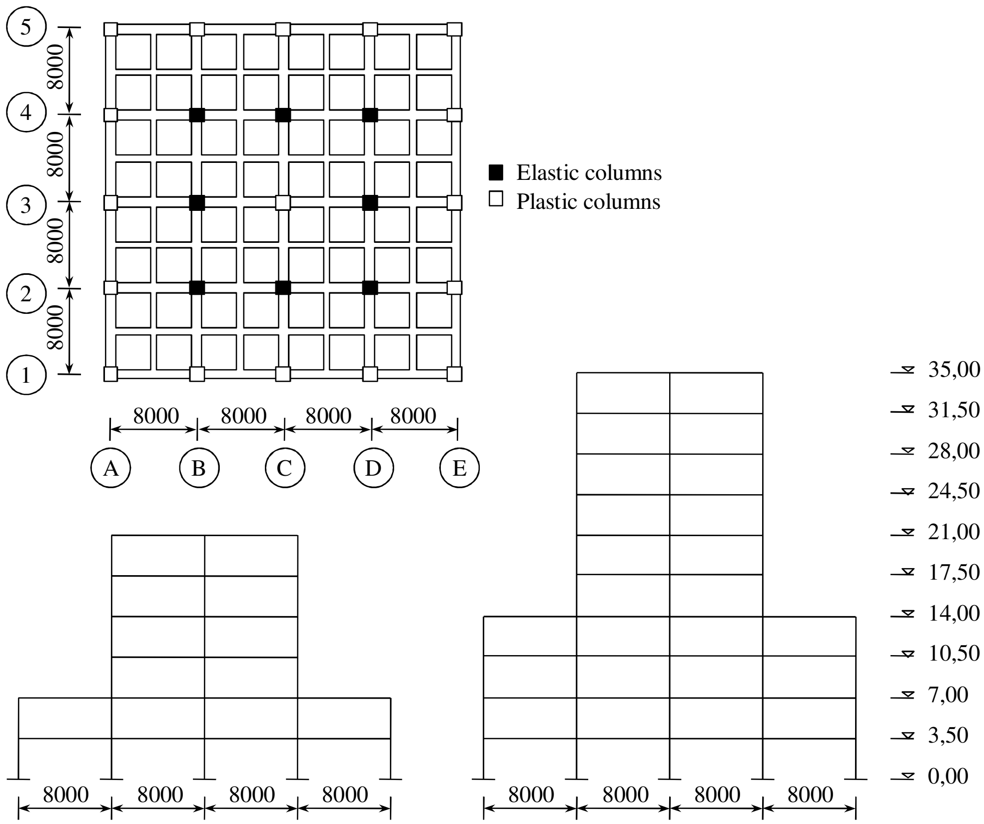

Figure 4: Structural plan and elevation.

The performance of the observed structures are determined by nonlinear time history analysis using RUAUMOKO 3D (Carr 2002). The ground acceleration used for the time history analysis is the spectrum of consistent ground acceleration modified from N-S component of El-Centro 1940. The modification is achieved using RESMAT, a program developed at Petra Christian University, Surabaya.

The acceptance criteria for evaluating structural performance are based on story drift and failure mechanism of the structure. The maximum drift specified by the Indonesian standard is 0.02. And the maximum damage index at the plastic hinge is determined based on ATC-40 which are 0.25, 0.40, and 1.00 for immediate occupancy, life safety, and collapse prevention respectively.

5. STRUCTURAL PERFORMANCE

The structural performances based on drift and damage index are shown in Table 1, 2 and 3. Based on drift and beam damage index parameter, it can be seen that all structures having good performance at the targeted seismic level (500 years return period), although at lower level their drifts and damage index are higher than the maximum value determined by ATC 40 (Table 1 and 2).

The plastic columns performed well at any level of earthquake loadings (Table 3). As expected, some plastic hinges occur at the assigned columns (plastic columns), and the damage index are still in acceptable value.

Table 1: Structural performance based on drift (%).

Return Period (years)	Structures	Performance Level							
		Serviceability Limit State		Damage Control Limit State		Safety Limit State		Unacceptable	
		Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6
50	6-story			0.56	0.59				
	10-story			0.78	0.80				
200	6-story			0.95			1.14		
	10-story					1.24	1.28		
500	6-story					1.33	1.60		
	10-story					1.41	1.74		
1000	6-story					1.65			2.07
	10-story					1.58			4.42
Maximum drift		0.50		1.00		2.00		> 2.00	
		Basic objectives							

Table 2: Structural performance based on damage index of beams.

Return Period (years)	Structures	Performance Level							
		Serviceability Limit State		Damage Control Limit State		Safety Limit State		Unacceptable	
		Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6
50	6-story	0.17	0.10						
	10-story		0.14	0.29					
200	6-story		0.23			0.42			
	10-story				0.34	0.50			
500	6-story					0.59	0.46		
	10-story					0.62	0.72		
1000	6-story						0.59	1.07	
	10-story					0.80			5.61
Maximum damage index		0.10 – 0.25		0.25 – 0.40		0.40 – 1.00		> 1.00	
		Basic objectives							

Table 3: Structural performance based on damage index of plastic columns.

Return Period (years)	Structures	Performance Level							
		Serviceability Limit State		Damage Control Limit State		Safety Limit State		Unacceptable	
		Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6
50	6-story	---	---						
	10-story	0.04	---						
200	6-story	0.11	---						
	10-story	0.17	0.12						
500	6-story		0.17	0.21					
	10-story	0.19			0.29				
1000	6-story			0.35	0.25				
	10-story			0.28					1.89
Maximum damage index		0.10 – 0.25		0.25 – 0.40		0.40 – 1.00		> 1.00	
		Basic objectives							

Table 4: Structural performance based on damage index of elastic columns.

Return Period (years)	Structures	Performance Level							
		Serviceability Limit State		Damage Control Limit State		Safety Limit State		Unacceptable	
		Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6	Zone 2	Zone 6
50	6-story	---	---						
	10-story	---	---						
200	6-story	0.02	0.23						
	10-story	0.03	0.23						
500	6-story	0.20			0.36				
	10-story	0.06					0.52		
1000	6-story			0.37			0.71		
	10-story	0.13							3.34
Maximum damage index		0.10 – 0.25		0.25 – 0.40		0.40 – 1.00		> 1.00	
		Basic objectives							

Unfortunately, the elastic columns are not performed well as expected due to the presence of some plastic hinges. It indicates that the value of the Magnification Factor is not suffice to protect the elastic column. The condition is also worsen by the changes of columns dimension at the set-back region where the stress concentration take place resulting the partial side sway mechanism could not be achieved.

Furthermore, the fail of elastic columns to maintain its elastic condition leadings to the need of further research on the application of Magnification Factor (MF) including the empirical formula to determine the plastic period, $T_{plastic}$ in Equation (3). Should be noted here that both equations are derived from regular structures which its response are more simple to be predicted than in the case of irregular structures. Therefore, the use of both equations needs to be improved for irregular structures.

6. CONCLUSIONS

Although the observed stuctures satisfy the drift limitation, but the proposed Partial Capacity Design (PCD) fails to meet the partial beam side sway mechanism due to improper use of the Maginification Factor and columns dimension choice. The use of Magnification Factor (MF) should be applied with some caution especially on the case of irregular structures.

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