

PARTIAL CAPACITY DESIGN, A CASE STUDY OF STRUCTURE WITH VERTICAL SET-BACK

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ABSTRACT

A new design method named the Partial Capacity Design Method (PCDM) has been proposed by the Authors. In this method instead of side sway mechanism, partial side sway mechanism is employed, in which for a certain seismic load level (named target seismic load) some columns are allowed to develop plastic hinges while some selected columns are to remain elastic except at the base. To ensure these selected columns remain elastic, these columns are designed to resist magnified internal forces. The internal forces due to the nominal seismic load are multiplied by a certain magnification factor, f . The performance of several symmetrical fully ductile concrete moment resisting frame designed in accordance with the latest Indonesian Seismic Code (SNI 03 1726-2002) using the proposed method has been presented elsewhere. In this paper the proposed method (PCDM) is used to design structures with vertical set-back. The seismic performances of the structures are evaluated using dynamic non-linear time history analysis. The results show that under the intended seismic load level (target seismic load), the selected columns remain elastic as expected. The structures performed very well in accordance to the criteria suggested in the Asian Concrete Model Code (ACMC), however one should be very careful not to overdesign the beams connecting to the selected columns.

Keywords: Partial Capacity Design Method, magnification factor, seismic performance

ABSTRAK

Suatu cara perencanaan baru yang dinamakan *Partial Capacity Design Method (PCDM)* telah diusulkan oleh para penulis dalam beberapa kesempatan. Dalam PCDM, pada saat struktur menerima beban seismik tertentu (dinamakan beban seismik target) hanya beberapa kolom yang dipilih direncanakan tetap elastis kecuali pada dasar kolom, pada kolom yang lain diperbolehkan terjadi sendi plastis. Dengan demikian pola keruntuhan yang terjadi adalah pola *partial side sway mechanism*. Untuk meyakinkan kolom-kolom yang dipilih tetap elastis, kolom-kolom ini direncanakan menggunakan gaya dalam akibat beban gempa nominal yang dikalikan dengan suatu faktor pengali, f . Perilaku struktur beton bertulang simetris yang direncanakan sesuai dengan peraturan gempa (SNI 03 1726-2002) menggunakan PCDM telah dipresentasikan dalam kesempatan lain. Dalam makalah ini beberapa struktur dengan *vertical set back* direncanakan dengan PCDM kemudian perilaku seismik struktur ini diperiksa dengan menggunakan analisa dinamik riwayat waktu non-linear. Hasil yang didapat menunjukkan bahwa perilaku bangunan yang ditinjau terhadap beban seismik target dapat memenuhi persyaratan yang ditetapkan dalam *Asian Concrete Model Code (ACMC)*. Kolom yang dipilih ternyata tetap dalam keadaan elastis, tetapi harus diingat bahwa memberikan tulangan yang berlebihan pada balok yang merangka pada kolom elastis yang dipilih dapat menimbulkan masalah.

Kata kunci: *Partial Capacity Design Method*, faktor pengali, performa seismik

1. INTRODUCTION

The Capacity Design Method (CDM) is a well accepted design procedure for earthquake resistant design. CDM employs “strong column-weak beam” design philosophy where the failure mechanism expected is the so called Side Sway Mechanism (Figure 1). Applying CDM implies that the columns can only be designed after the beams are designed. This is not very practical in real world of design practice. Several efforts have been made to overcome this shortcoming (Lumantarna et.al.,1994, 1997, 1998,2004; Chandra and Dhannyanto, 2003; Saputra and Soegiarto, 2005). In the last development, Muljati and Lumantarna (2007, 2008) explored and suggested alternative design methods called Partial Capacity Design Method (PCDM) which allowed partial side sway mechanism, shown in Figure 2 (Paulay, 1995). In the proposed method, plastic hinges were allowed to develop in the interior columns, while no plastic hinge was allowed in the exterior columns, except at the base of the columns. To ensure that the perimeter columns remained elastic due to the target seismic load, the perimeter columns were designed to resist magnified internal forces due to the nominal earthquake load multiplied by a certain magnification factor. Muljati and Lumantarna (2007, 2008) developed a certain formula to obtain a magnification factor, f , to be used in increasing the perimeter columns strength. The performance of several symmetrical fully ductile concrete moment resisting frame designed in accordance with the latest Indonesian Seismic Code (SNI 03 1726-2002) using the proposed method has been presented elsewhere (Mulyati and Lumantarna, 2007, 2008, 2009a, 2009b).

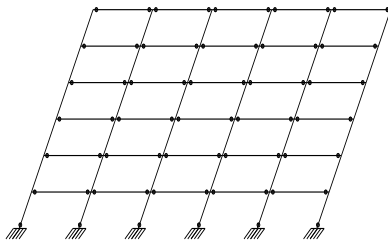


Figure 1. Sidesway Mechanism

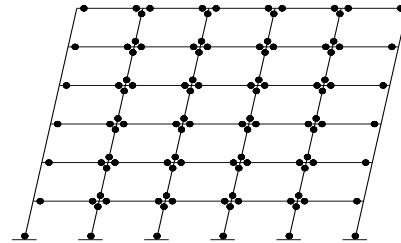


Figure 2. Partial Sidesway Mechanism

Recently Muljati and Lumantarna (2011) applied PCDM to structures with vertical set-back as shown in Figure 3.

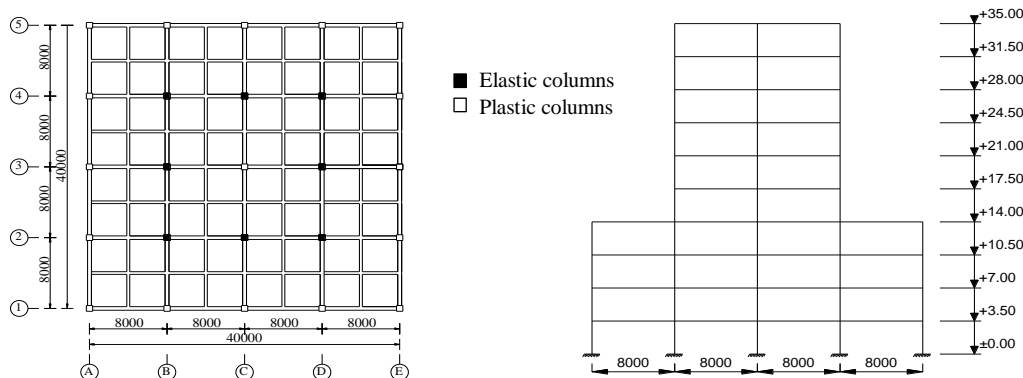


Figure 3. Building with vertical set-back, considered in Mulyati and Lumantarna (2011)

Columns 2-B,C,D; 3-B,D; and 4-B,C,D which are not at the perimeter are selected to be the elastic columns. This building is assumed to be built in Zone 6 of the Indonesian Earthquake code (SNI 03 1726-2002). Muljati and Lumantarna (2011) reported that plastic hinges developed in some “elastic perimeter” columns. The present authors suspect that since the magnification factor formula is developed based on a certain design practice, the failure could be caused by “improper” design practice. The present authors revisit the structures used by Muljati and Lumantarna (2011) and refined the design.

2. PARTIAL CAPACITY DESIGN

PCDM offers some convenience compared to the CDM because columns can be designed before the design of beams are completed. The design procedure of PCDM is shown in Figure 4.

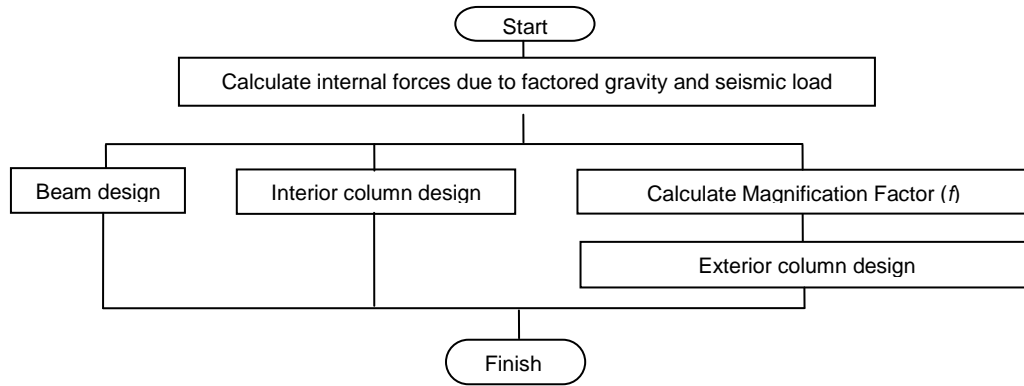


Figure 4. Flowchart of PCDM

2.1. Magnification factor, f

Assuming that the interior columns can only take the shear force due to the nominal seismic load and some reserve strength of the structure, Muljati and Lumantarna (2008, 2009) proposed the magnification factor, f , for the exterior column as follows:

$$S_{ex}^T = S_{ex}^N * f,$$

$$where f = \frac{\left(\frac{C^T}{C^{500}} \right) \times \mu - 1.6 \times \left(\frac{C_{in}^T}{C_{in}^{500}} \right) \times R_{in}^N}{\left(\frac{C_{ex}^T}{C_{ex}^{500}} \right) \times R_{ex}^N} \quad (1)$$

In Equation 1, S_{ex}^N is the shear force in the individual exterior column due to the nominal seismic load, which after multiplication by the magnification factor, f becomes S_{ex}^T the shear force in the same exterior column due to the target seismic load. While n_{ex} is the total

number of the exterior column; n_{in} the total number of the interior column; R_{in}^N and R_{ex}^N are respectively the ratio of the interior and exterior columns' base shear to the total base shear due to the nominal seismic load.

Target seismic load can be defined as the level of seismic load where the structure is expected to be in the safety limit state. Further, C^T and C^{500} are the spectral acceleration due to the target seismic load and five hundred years return period earthquake respectively, and μ the structure's ductility.

2.2. Target Spectral Acceleration, C^T

Since during the application of the target seismic load the structure is expected to be already in the non-linear stage, the target spectral acceleration C^T should be obtained from the non-linear/plastic response spectrum. The non-linear response spectrum can be generated if the effective damping factor, β_{eff} , can be predicted (Susanto, 2009). Alternately C^T can also be obtained if one can predict the period of the structure in the non-linear stage (plastic period, T_{pl}). Figure 5 shows the typical result of a static pushover non-linear analysis using the Capacity Spectrum Method (ATC40, 1996).

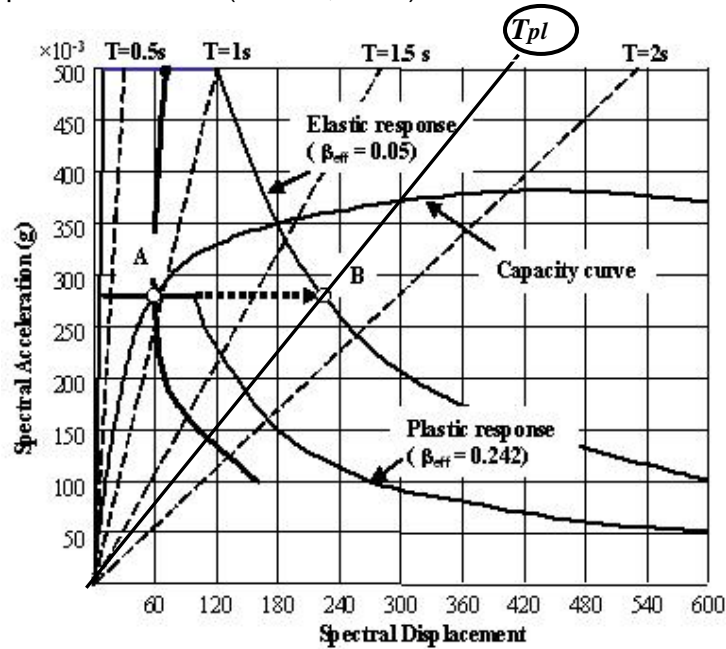


Figure 5. Development of the Plastic Period, T_{pl}

Figure 5 shows the elastic response spectrum of the target seismic load and reduced “plastic” response spectrum (demand spectrum). The intersection between the capacity spectrum and demand spectrum, “the performance point” is labeled as point A. The demand spectrum in this case is an elastic response spectrum considering effective damping β_{eff} , due to plasticity, thus “the plastic response spectrum”. In Figure 5, the plastic response

spectrum has an effective damping coefficient β_{eff} , of 0.242. The intersection of a horizontal line draws from point A with the ordinate gives the plastic spectral acceleration C^T . The intersection of the horizontal line with elastic response spectrum of the target seismic load (point B) gives the so called non-linear/plastic period, T_{pl} . Knowing the plastic period T_{pl} , the plastic spectral acceleration, C^T , can be obtained from the elastic response spectrum. Reni and Tirtalaksana (2008), Kusuma and Wibowo (2008), and Muljati and Lumantarna (2008) based on observations of the elastic and plastic natural period (T_e and T_{pl} respectively) of previous structures suggested a correlation between the elastic and the plastic natural period as:

$$T_{pl} = 2.969 T_e + 0.313 \quad (2)$$

3. SEISMIC PERFORMANCE OF BUILDING DESIGNED WITH THE PCDM

In this study buildings with vertical set-back used by Muljati and Lumantarna (2011) were redesigned. Figure 6 shows the plan and elevation of the ten-story building. Columns 2-B,C,D; 3-B,D; and 4-B,C,D are selected to be the elastic columns. These buildings are assumed to be built in Zone 6 of the Indonesian Earthquake code (SNI 03 1726-2002).

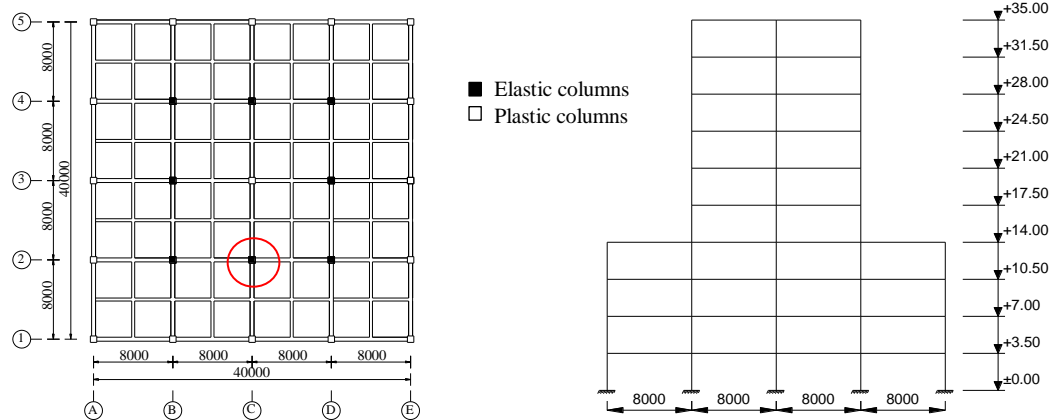


Figure 6. Structural Plan and Elevation of ten-story building

The present study refines the beam design, for example, the beams connected to column C2 (indicated by circle in the structural plan) at the level of setback are refined as shown in Table 1.

Table 1. Comparison of the reinforcements used in this study and the previous study (Muljati and Lumantarna, 2011)

Beam connected to C8	Location	Present study		Muljati and Lumantarna (2011)	
		Left	Right	Left	Right
B11	Top	6D19	11D19	12D19	12D19
	Bottom	3D19	6D19	6D19	6D19
B19	Top	13 D19	12D19	14D19	14D19
	Bottom	7D19	6D19	8D19	8D19
B20	Top	12D19	13D19	14D19	14D19
	Bottom	6D19	7D19	8D19	8D19
B28	Top	13D19	8D19	14D19	14D19
	Bottom	7D19	4D19	8D19	8D19

: end of the beam which is connected to column C2

The performance of these buildings are tested to static non-linear pushover analysis (ATC40, 1996, Krawinkler, 1994, 1996, Boen, 1999) and non-linear time history analysis. The static non-linear pushover analysis is performed using ETABS-nonlinear (Habibullah, 1998) with lateral load based on first mode shape. The non-linear time history analysis is performed using RUAUMOKO 3D (Carr, 2001, 2002). The hinge properties of the beams and columns are obtained using ESDAP (Lidyawati and Pono, 2003) a program developed at Petra Christian University, Surabaya based on the algorithm proposed by D.J. King (1986). The ground acceleration used for the time history analysis is spectrum consistent ground acceleration modified from the N-S component of El-Centro 1940. The modification is achieved using RESMAT (Lumantarna and Lukito, 1997), a program developed at Petra Christian University, Surabaya. The modified ground acceleration and the response spectrum are shown in Figure 7.

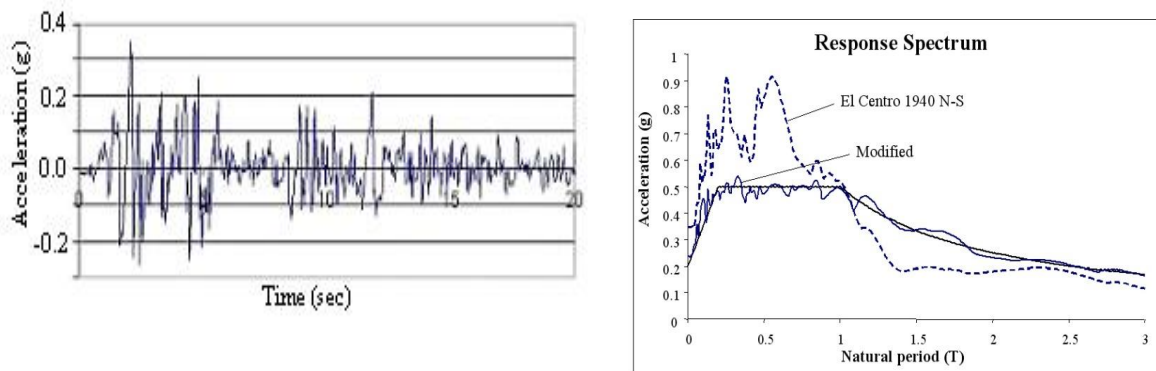
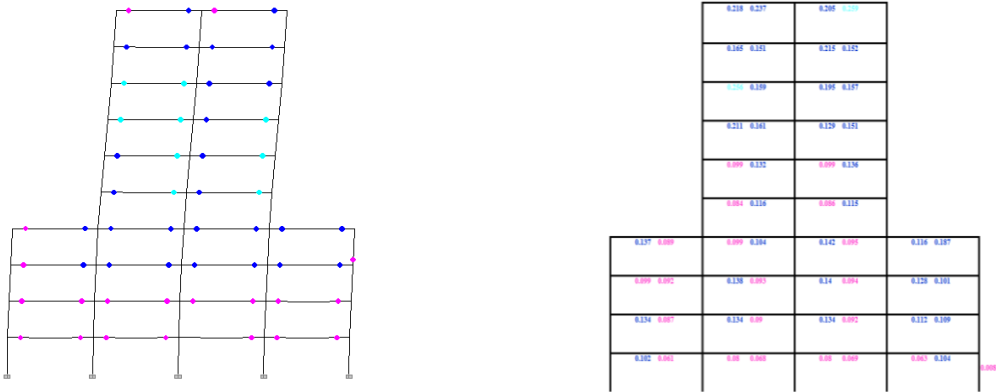


Figure 7. Modified seismic record and the response spectrum

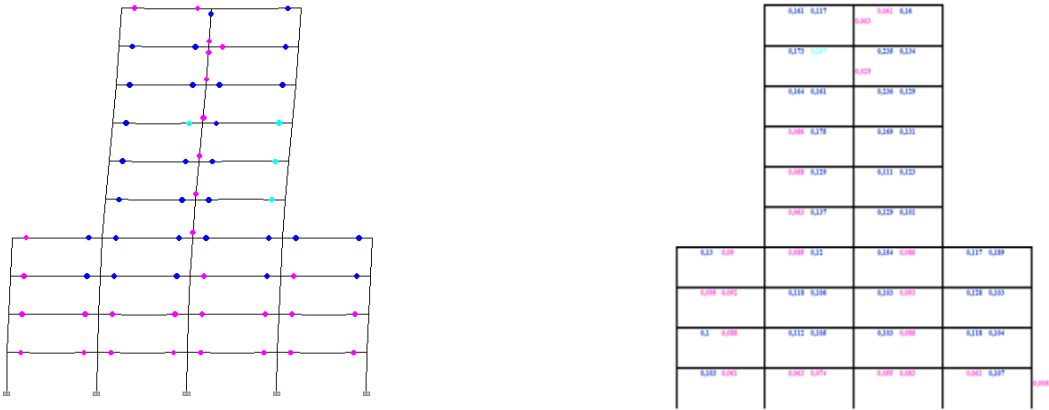
3.1. Plastic Hinges Location

Figures 8 and 9 show typical result of the analysis showing the plastic hinges location due to the application of a 500 years return period ground acceleration, which is also the target seismic load in this case. Complete information can be found in Wijoyo and Teddy (2011). Figure 8(a) and (b) show the plastic hinges location on the exterior frame of a ten-story four-

bay (H-10.4) building as analyzed using the static non-linear pushover analysis and the non-linear time history analysis respectively. Figure 9(a) and (b) plastic hinges on the interior frame of the same building. Dots in figures represent plastic hinges and numbers represent damage indices.



(a) Pushover (b) Time History
Figure 8. Plastic hinges on Exterior Frame of 10-story 4-bay building (H-10.4)

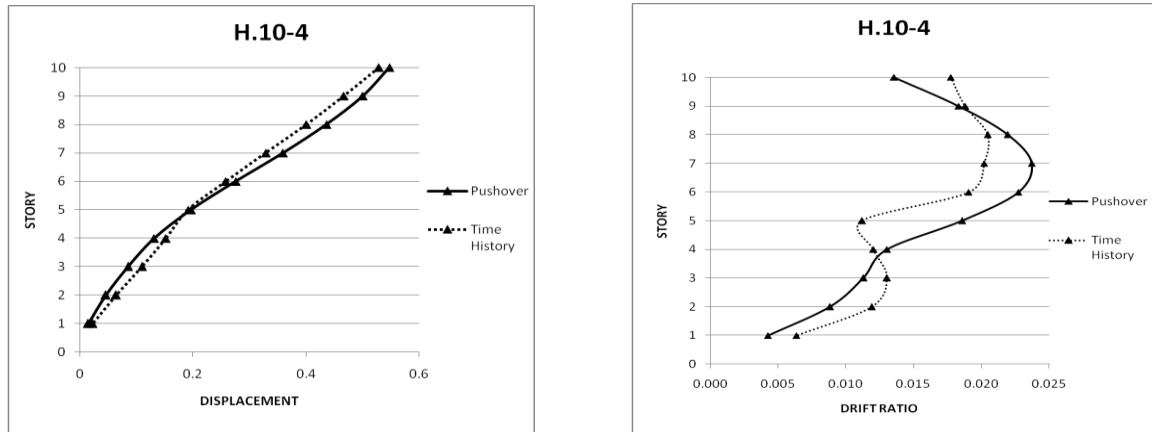


(a) Pushover (b) Time History
Figure 9. Plastic hinges on Interior Frame of 10-story 4-bay building (H-10.4)

3.2. Displacement and Drift

Figure 10 shows typical result of the deformations of the structures due to the target seismic load, which in this case is set as a 500 years return period ground acceleration. Figure 9(a) and (b) show respectively, the displacement and drift ratio of the ten-story four-bay building

(H-10.4) as analyzed using the static non-linear pushover analysis and the non-linear time history analysis.



(a) displacement (b) drift ratio
Figure 10. Displacement and drift ratio of 10-story 4-bay building (H-10.4)

4. CONCLUSION

The results of this research show that no plastic hinges occurred in elastic columns at the target seismic load (500 years return period ground acceleration), thus the partial side sway mechanism is well satisfied. However, since the columns are not designed using the capacity of the beams connected to them, one should be very careful and not place excessive reinforcement in the beams, only minimum round ups should be applied.

5. REFERENCES

- ATC 40 (1996), *"Seismic Evaluation and Retrofit of Concrete Buildings"*, Volume I. Applied Technology Council, California, USA.
- Atmadja, K.G. and Wijaya, B. (2009), *"Evaluasi Kinerja Bangunan Dengan Metode Pseudo Elastis pada Wilayah 6 Peta Gempa Indonesia"*, Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Boen, T. (1999), *"Dasar-dasar Analisa Pushover"*, Proc. Seminar Nasional Teknik Sipil, Universitas Katolik Parahyangan, Bandung, Indonesia, pp. 2.01-2.14.

- Buntoro, I.Y. and Welyianto, A. (2009), "*Evaluasi Kinerja Bangunan Dengan Metode Pseudo Elastis pada Wilayah 2 Peta Gempa Indonesia*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia
- Carr, A.J. (2001), Ruaumoko, "*Inelastic Dynamic Analysis*", 3-Dimensional Version, University of Canterbury, New Zealand.
- Carr, A.J. (2002), "*Ruaumoko Computer Program Library*". University of Canterbury, New Zealand.
- Chandra, A. and Dhannyanto (2003), "*Alternatif Perencanaan Struktur Rangka Beton Bertulang dengan Pseudoelastis*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Habibullah, A. (1998), ETABS, "*Three Dimensional Analysis and Design of Building Systems, Computer and Structures, Inc.*", Berkeley, California, USA.
- King, D.J. (1986), "*Computer Programs for Concrete Column Design*", Research Report, University of Canterbury, New Zealand.
- Krawinkler, H. (1994), "*Static Pushover Analysis, SEAONC 1994 Fall Seminar on The Developing Art of Seismic Engineering*", California, USA, pp. 1-24.
- Krawinkler, H. (1996), "*Pushover Analysis: Why, How, When and Where Not to Use It*", Proc. 65th Annual Convention SEAOC, Maui, Hawaii, USA, pp. 17-36.
- Kusuma, A. and Wibowo, Z.Y. (2008), "*Evaluasi Kinerja Struktur 4 dan 10 Lantai yang Didesain Sesuai Pseudo Elastis dan SNI 03-2847-2002 di Wilayah 6 Peta Gempa Indonesia*". Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Lidyawati, and Pono, G.B.W. (2003), "*Penyempurnaan Program Komputer untuk Desain Beban Lentur dan Aksial serta Analisa Momen Kurvatur Penampang Beton Bertulang*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Lumantarna, B. (1998), "*Batasan Pemakaian Perencanaan Pseudo Elastis Menggunakan Satu Pasang Kolom Tepi*", Dimensi, vol 23/sip, April 1998, pp. 60-65.
- Lumantarna, B. and Francica, C. (1994), "*Perencanaan Kapasitas Alternatif, Suatu Studi Pendahuluan*", Proc. of the International Conference on Modern Design and Construction for Safety, Economy, and Durability, Petra Christian University, Surabaya, Indonesia.
- Lumantarna, B. and Lukito, M. (1997), "*Resmat, Sebuah Program Interaktif untuk Menghasilkan Riwayat Waktu Gempa dengan Spektrum Tertentu*", Proc. HAKI Conference 1997, Jakarta, Indonesia, pp. 128-135.
- Lumantarna, B., Andriono, T., Chandra, A., Dhannyanto (2004), "*Alternatives to the Capacity Design Method, a Preliminary Proposal*", Proc. of the 18th Australasian Conference on the Mechanics of Structures and Material; ACMSM18, Perth, 1-3 December 2004. Leiden: Balkema.
- Lumantarna, B., Tindrawati, and Wijaya, J. (1997), "*Studi Pendahuluan tentang Perencanaan Seismic Beton Bertulang Menggunakan Metode Pseudo Elastis*",

- HAKI Conference on Civil and Structural Engineering, Jakarta, Indonesia, pp. 102-115.
- Muljati, I. and Lumantarna, B. (2007), "*Partial Capacity Design, an Alternative to the Capacity Design Method*", Proceedings of the 19th Australasian Conference on the Mechanics of Structures and Materials; ACMSM19, Christchurch, New Zealand, pp. 409-414.
- Muljati, I. and Lumantarna, B. (2008), "*Performance of Partial Capacity Design on Fully Ductile Moment Resisting Frame in Highly Seismic Area in Indonesia*", Eleventh East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-11) "Building a Sustainable Environment", Taipei, Taiwan.
- Muljati, I. and Lumantarna, B. (2009a and b), "*Partial Capacity Design, An Alternative to The Capacity Design Method*", Guest Lecture on 17 July 2009 in Carleton University, Ottawa, Canada, also in HAKI Conference, 11-12 Agusts 2009, Jakarta, Indonesia.
- Muljati, I. and Lumantarna, B. (2011), "*Seismic Performance of Structure with Vertical Geometric Irregularity Designed Using Partial Capacity Design*", 2nd International Conference on Earthquake Engineering and Disaster Mitigation (ICEEDM), 19 July 2011, Surabaya, Indonesia.
- Paulay, T. (1995), "*Special Issues in Seismic Design*", Structural Engineering International, Volume 5: 160-165.
- Reni, S. and Tirtalaksana, I. (2008), "*Evaluasi Kinerja Struktur 6 dan 8 Lantai yang Didesain Sesuai Pseudo Elastis dan SNI 03-2847-2002 di Wilayah 6 Peta Gempa Indonesia*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Saputra, R.H. and Soegiarto, A. (2005), "*Penentuan Faktor Pengali untuk Perencanaan Pseudo Elastis pada Struktur Rangka Penahan Momen Khusus*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- SNI 03 1726-2002 (2002), "*Standar Perencanaan Ketahanan Gempa untuk Struktur Gedung, SNI 03 1726*", Departemen Pemukiman dan Prasarana Wilayah, Bandung, Indonesia.
- Susanto, T. (2009), "*Studi Faktor Pengali Kapasitas Kolom Eksterior dalam Perencanaan Pseudo Elastis*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.
- Wijoyo, H. and Teddy, S. (2011), "*Evaluasi Metode Desain Pseudo Elastis untuk Bangunan Tidak Beraturan 6- dan 10-Lantai dengan Vertical Set-Back 50% di Wilayah 6 Peta Gempa Indonesia*", Undergraduate Theses, Civil Engineering Department, Petra Christian University, Surabaya, Indonesia.