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EVALUATION OF PREVIOUS AND CURRENT PERFORMANCE BASED ANALYSIS METHODS

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ABSTRACT :

In last decades, through further development of computer technology in civil engineering, the more complex seismic analysis became possible and accuracy of the analysis is increased. ATC 40, FEMA 273, 274, 356 and recently 440 are the most commonly used resources for seismic analysis procedures enduring with computing in civil engineering. These resources explain the two common seismic analysis methods named as performance based analysis, which are “Capacity Spectrum Method” and “Displacement Coefficient Method”. With FEMA 440, these two methodologies are renewed by the experiences of the engineers. The objective of this study is to evaluate the new and previous two common performance based analysis methods for reinforced concrete structures by comparing time history analysis results. In the present study, the procedures of Capacity Spectrum Method and Displacement Coefficient Method are reviewed in detail. The methods are compared for a selected reinforced concrete structure, a 4-story reinforced concrete building. The selected building is considered to be in a high seismicity region. Maximum inelastic displacement and performance level of the reinforced concrete building are determined for each method. In the conclusion, the results of the both current and previous methods are presented and compared with time history analyses according to the displacement demands of the building.

KEYWORDS: Performance Evaluation, Capacity Spectrum Method, Displacement Coefficient Method

1. INTRODUCTION

In the past ten years, there has been a rise in earthquake related losses. The estimated losses are very larger than the previous years. FEMA’s publications related to earthquake losses have become an increasing percentage of its disaster assistance budget. Predictions are that future single earthquakes. Through advances in computer analysis techniques as the computer technology, nonlinear structural analysis becomes possible (Irtem et al., 2007). FEMA is publishing some pre-standards for increasing the earthquake resistance of the existing and new structures. FEMA proposes some methodologies by using pushover analysis as nonlinear static analysis even though nonlinear time history analysis has more accurate results on computing seismic demands. With FEMA 440, these two methodologies are renewed by the experiences of the engineers who are dealing with the performance based analysis. The new FEMA is presented is published by the aim of more accurate seismic assessment (ATC40, 1996; FEMA273-274, 1997; FEMA356, 2000; FEMA440, 2005).

The objective of this study is to evaluate the performance based analysis methods. For this reason, new and previous capacity spectrum and displacement coefficient methods are examined and the results of the analysis on a selected sample building are compared. The performance of the buildings under earthquake risk is researched. First, push over analysis is realized for the sample structure. Then, performance based methodologies are conducted using the nonlinear pushover analyses results. The results from the analyses are compared with each other. As a baseline for comparison of the methodologies, time history analysis as known the most reliable structural analysis is performed and compared with the performance based analyses results (FEMA440, 2005).

2. CAPACITY SPECTRUM METHOD

Capacity spectrum method is one of the nonlinear static analysis methods which has been developed for estimating displacements and comparing the capacity of a structure with the demands of earthquake ground motion on it. The inelastic strength and displacement spectra used for the determination of an earthquake demand can be obtained by nonlinear analysis of inelastic SDOF systems. This method recognizes that when the structure is shaken beyond of its yield point, its effective damping and its effective period will increase. The maximum structural response is estimated to be the point where the capacity curve crosses the demand spectrum. This method aims to reduce the 5% damped elastic spectrum of the ground motion to a lower spectrum that is in agreement with the structure's response. By determining a maximum displacement and acceleration on the capacity curve, that is in agreement with the ground motion demand at the higher damping and longer period that the structure experiences, the structural response to a given ground motion can be estimated. In FEMA 440, the methodology is renewed. The new FEMA is presented is published by the aim of more accurate seismic assessment (FEMA 440, 2005).

2.1. New Methodology

The peak displacement of a nonlinear system is estimated as the intersection of the capacity curve and an elastic response spectrum that is reduced to account for energy dissipated by the yielding structure. Effecting damping ratio could be calculated by these equations (1-3). The Spectral accelerations and displacements is found by Equation (4). The determination of performance point is given in figure 1 (FEMA 440, 2005).

For μ<4.0; $$\beta_{eff} = 4.9(\mu-1)^2 - 1.1(\mu-1)^3 + \beta_0 \tag{2.1}$$

For 4.0 <μ<6.5; $$\beta_{eff} = 14 + 0.32(\mu-1) + \beta_0 \tag{2.2}$$

For μ>6.5; $$\beta_{eff} = 19\left[\frac{0.64(\mu-1)-1}{[0.64(\mu-1)]^2}\right]\left(\frac{T_{eff}}{T_0}\right)^2 + \beta_0 \tag{2.3}$$

Where β_{eff} : effective damping ratio, β_0 : equivalent viscose damping ratio and $\mu = \frac{d_{pi}}{d_y}$ which is ductility.

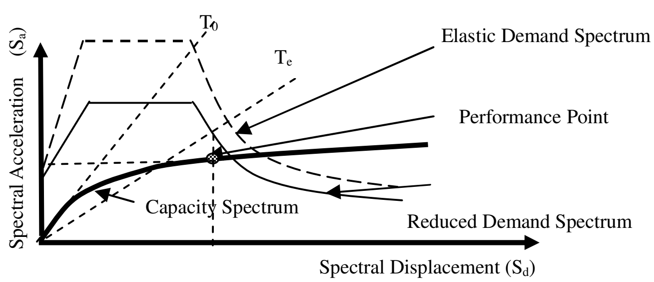


Figure 1 Determination of performance point by using new methodology

$$(S_a)_\beta = \frac{(S_a)_{\%5}}{B(\beta_{eff})} \tag{2.4}$$

$$S_d = \frac{T_e}{4\pi^2} S_a \tag{2.5}$$

2.2. Previous Methodology

The ATC-40 report details the Capacity-Spectrum Method, whereby modal displacement demand is determined from the intersection of a capacity curve (ATC40, 1996). The previous methodology is close to new one with some graphical approach differences. The performance point is determined in previous one by showing in figure 2. In the previous methodologies the equation (2.6 and 2.7) is used to convert the system into single degree of freedom system. Reduce of the demand spectrum is realized by the equations (2.8-2.9).

$$\alpha_1 = \frac{\left[\sum_{i=1}^{N}(w_i\phi_{i1}/g)\right]^2}{\left[\sum_{i=1}^{N}(w_i/g)\right]\left[\sum_{i=1}^{N}(w_i\phi_{i1}^2/g)\right]} \tag{2.6}$$

$$PF_1 = \left[\frac{\sum_{i=1}^{N}(w_i\phi_{i1}/g)}{\sum_{i=1}^{N}(w_i\phi_{i1}^2/g)}\right] \tag{2.7}$$

Where $\mathbf{S_a}$**:** Spectral acceleration, $\mathbf{S_d}$**:** Spectral displacement, V_T**:** Total Shear force, $\boldsymbol{\delta}_{\mathbf{max}}$**:** Roof Displacement, **W:** Total building weight.

$$SR_A = \frac{3.21 - 0.68\ln(\beta_{eq})}{2.12} \tag{2.8}$$

$$SR_V = \frac{2.31 - 0.41\ln(\beta_{eq})}{1.65} \tag{2.9}$$

$$\beta_{eq} = \frac{63.7\kappa(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} + 5 \tag{2.10}$$

$$0.33 \le \kappa \le 1.00$$

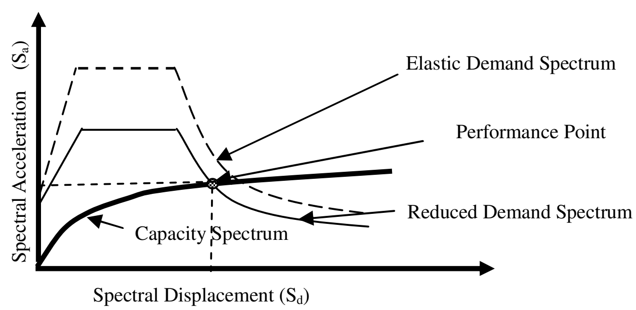


Figure 2 Determination of performance point by using previous methodology

3. DISPLACEMENT COEFFICIENT METHOD

Displacement Coefficient Method estimates the maximum displacement by using ductility is. The Displacement Coefficient Method provides a direct numerical process for calculating the displacement demand. It does not require converting the capacity curve to spectral coordinates. The nonlinear force-displacement relationship between base shear and displacement shall be replaced with an idealized relationship to calculate the effective lateral stiffness, K_e, and effective yield strength, V_y, of the structure. This relationship shall be bilinear, with initial slope K_e and post yield slope K_s. Line segments on the idealized force-displacement curve shall be located using an iterative graphical procedure that approximately balances the area above and below the curve. The effective lateral stiffness, K_e, should be taken as the secant stiffness calculated at the base shear force equal to %60 of the effective yield strength of the structure. The effective fundamental period in the direction under consideration shall be based on the idealized force-displacement curve.

3.1. New Methodology

The target displacement is calculated in accordance with equation (3.1) given below (FEMA 440, 2005):

$$\delta_T = C_0 C_1 C_2 S_a \frac{T_e^2}{4\Pi^2} g \tag{3.1}$$

C_0: modification factor to relate spectral displacement of an equivalent single degree of freedom system to the roof displacement of multi degree of freedom system. C_1: Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response. C_2: Modification factor to represent the effect of pinched hysteretic shape, stiffness degradation and strength deterioration on maximum displacement response (FEMA 440, 2005).

$$\text{For } T_e < T_0, C_1=1.0 \quad \text{or, for } T_e = T_i (K_i/K_e)^{0.5} > T_0 \qquad C_1=1.0+\frac{R-1}{aT_e^2} \tag{3.2}$$

$$R = (S_a / g) / \left[(V_y C_0)/W\right] \tag{3.3}$$

3.2. Previous Methodology

In the previous one given in FEMA 356, there are some different equations comparing to new methodology. Where the K_e intersect the capacity curve should be 0.60 times K_e and K_s intersection. The target displacement is calculated in accordance with equation (3.4) as new methodology (FEMA 356, 2000).

$$\delta_T = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\Pi^2} g \tag{3.4}$$

$$\text{For } T_e \geq T_{0,} \quad C_1=1.0+\frac{R-1}{aT_e^2} \quad \text{else, } C_1=1.0 \tag{3.5}$$

$$\text{Where} \quad R = (S_a / g) / \left[(V_y C_0)/W\right] \tag{3.6}$$

$$C_3 = 1.0 + \frac{\alpha(R-1)}{T_e} \tag{3.7}$$

4. TIME HISTORY ANALYSIS

Time history analysis is known as the most accurate and reliable analysis methodology, since the actual earthquake loads are applied on the structure to get the real displacements of the structure (Li, 1996). Kocaeli data (ARC000), one of the effective earthquakes which occurred in August 1999 in Turkey with PGA 0.218g Soil type B, is used in the analyses. Data is taken from PEER page (http://peer.berkeley.edu). Idealization process (figure 3) is realized for obtaining demand spectrum of Kocaeli by Matlab (Matlab™ V6.13).

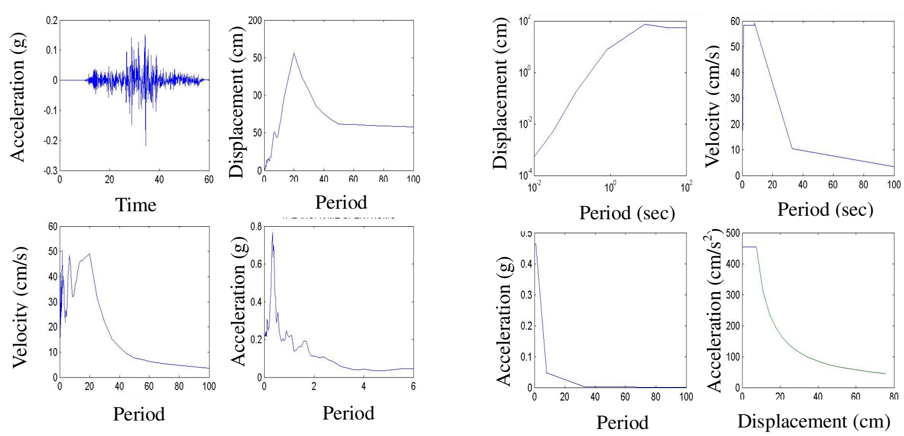


Figure 3 Idealization of Kocaeli, Turkey earthquake data

5. ANALYTICAL EXAMPLE

Here, to apply the performance based methods, an analytical example is given. The structure used in the analyses is 4-story and 12m height R/C building. The story weight is 10000kN. It is at the 1st zone and Class D soil type. The selected structure is dimensioned by SAP2000 (Wilson and Habibullah, 1998). In figure 4 and 5 selected structure is given in plan and section view respectively.

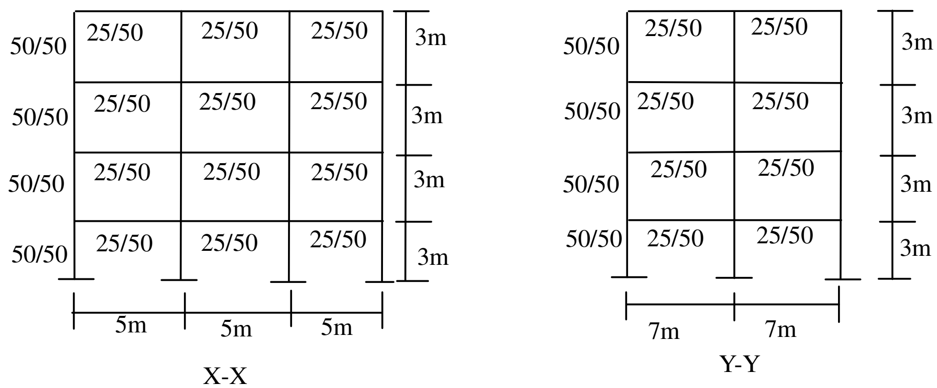


Figure 4 XX and YY Cross Sections of the sample 4-story structure

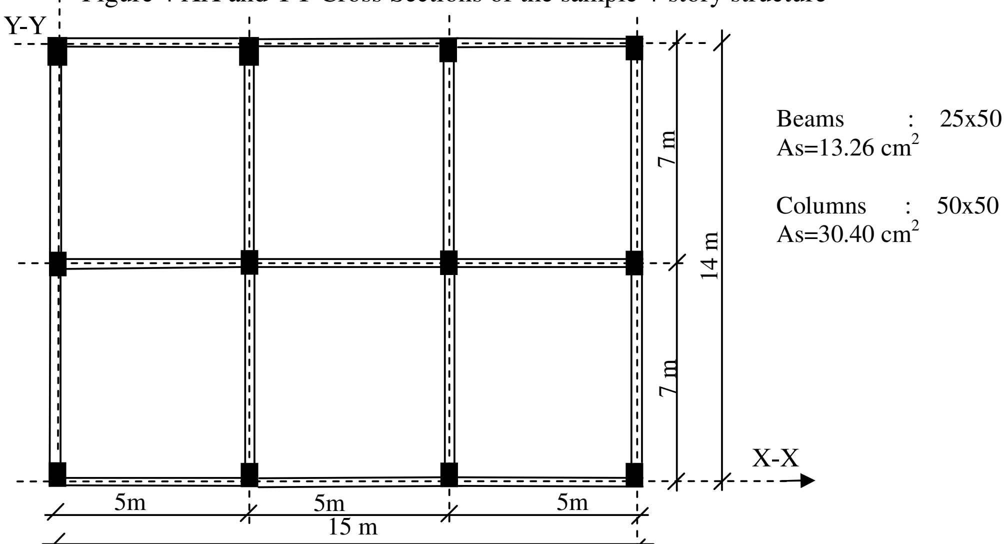
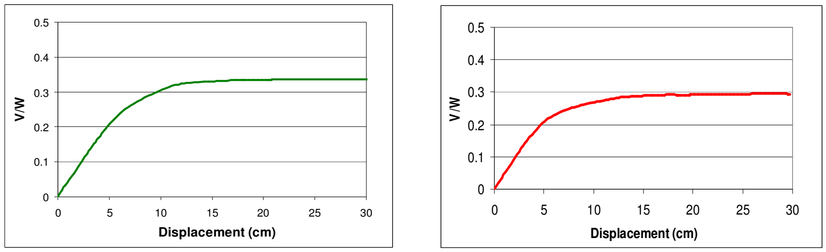


Figure 5. Plan view of the selected sample 4-story structure

5.1. Capacity Spectrum Method Analysis Results

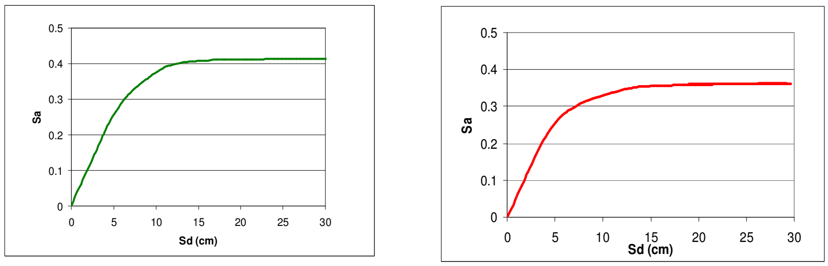
By using Capacity Spectrum Method, figure 6 and 7 are sketched in performance based analysis. In figure 8, Acceleration and demand spectrums are given for Class D soil type. The intersecting the capacity spectrum with demand spectrum for the determination of performance points is showed in figure 9. The pushover curves are sketched by using DRAIN 2D nonlinear program (Prakash and Powell, 1993).

By using New and previous Capacity Spectrum methods, performance points are determined. The performance points are determined as 11.5cm for X axis, and 10.8 cm for Y axis for new methodology. For previous one, 12.2cm for X axis, and 11.8 cm for Y axis.



a) Capacity Curve in X-X **b)** Capacity Curve in Y-Y

Figure 6. Capacity curves in X-X and Y-Y axis for selected R/C structure



a) Capacity Spectrum in X-X **b)** Capacity Spectrum in Y-Y

Figure 7. Capacity spectrums in X-X and Y-Y axis for selected R/C structure

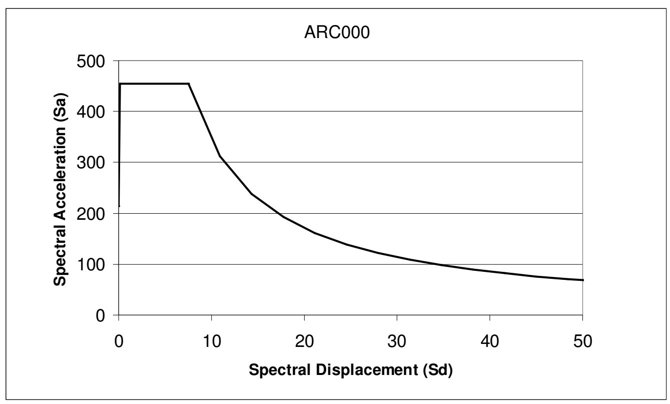
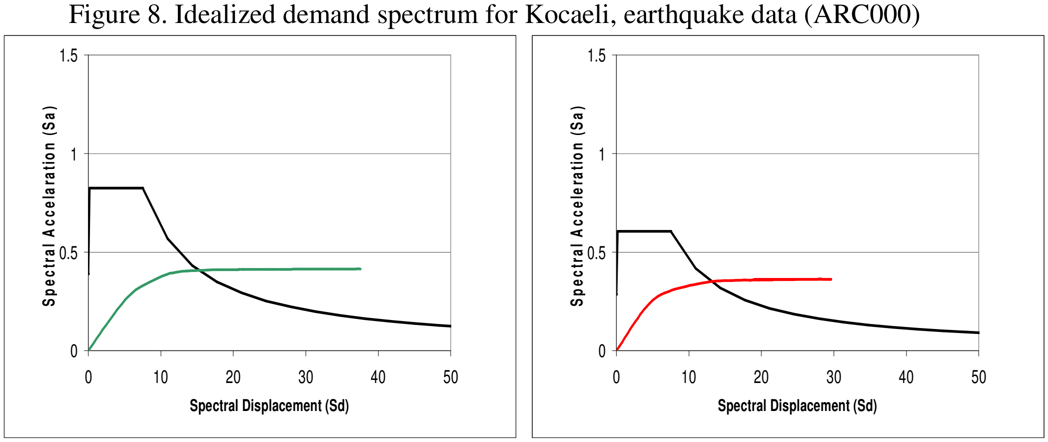


Figure 8. Idealized demand spectrum for Kocaeli, earthquake data (ARC000)

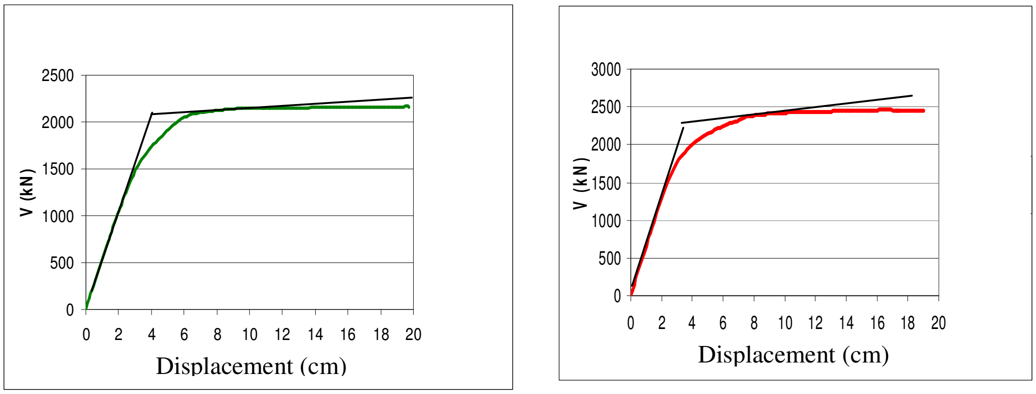


a) Intersection for X-X **b)** Intersection for Y-Y

Figure 9 Intersections determined by reduction of demand spectrum

5.2. Displacement Coefficient Method Analysis Results

Capacity curve is idealized in figure 10. The target displacements are determined with using these coefficients in X and Y axis respectively. Thus, performance points are defined in this aspect. Displacement coefficient method is pursued for this selected structure to define the structural performance. At the final step of the analyses, the displacement is found as 12.2 cm in X axis, and 11.6 cm in Y axis for new methodology. 14.6 cm in X axis, and 12.3 cm in Y axis for previous one.



a) capacity curve for X-X axis b) capacity curve for Y-Y axis

Figure 10 Idealization of capacity curves in displacement coefficient method

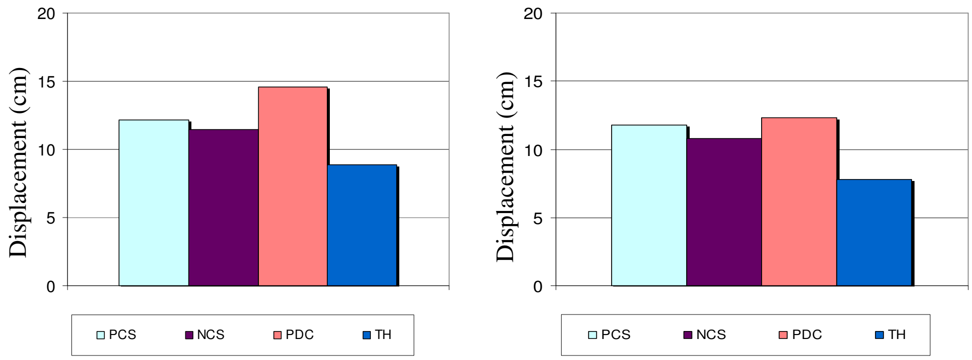
5.3. Time History Analysis Results

Nonlinear dynamic time history analysis has been employed to the selected sample structure by using Kocaeli, Turkey earthquake data. The actual earthquake loads are applied on the structure to determine the real displacements of the structure. Obtained maximum displacements are 8.9cm for X-X Axis; 7.8cm for Y-Y Axis.

6. CONCLUSIONS

In this study, new and previous Capacity Spectrum Method and Displacement Coefficient Method are taken into consideration as a performance based analysis methodology. After definition of the methodologies, an analytical application is realized for a selected sample R/C structure. After the methods are applied, the time history analysis is realized for the same sample structure for control. Performance points of selected R/C structure by using Capacity Spectrum Method are determined as, 11.5cm for X axis, and 10.8 cm for Y axis with the new methodology. For previous one, it is found as 12.2cm for X axis, and 11.8 cm for Y axis. Performance points of selected R/C structure by using Displacement Coefficient Method are determined as, 12.2 cm for X axis, and 11.6 cm for Y axis with new methodology. 14.6 cm in X axis, and 12.3 cm in Y axis for previous one. The maximum displacements obtained from time history analysis are 8.90 for X axis and 7.80 for Y axis.

In comparison of these methods, in Displacement Coefficient Method, target displacement is determined analytically without converting the capacity curve in capacity spectrum which is one of the easier parts of the method. However it is very possible to say that, those methods give close results in the analysis of symmetric structures as the selected one. Target displacement of selected structure determined with the new Displacement Coefficient Method is more than the new Capacity Spectrum Method. New Capacity Spectrum Method results and new Displacement Coefficient Method results are more than time history results as given in table 1. The all results are compared with each other and time history results as given in figure 11.The new capacity spectrum method gives closer results to the time history results regarding with the new and previous Displacement Coefficient Method and previous Capacity spectrum method. In Table 1, the observed displacements are given for comparison. Here, time history results are taken as reference point for comparison.



a) Comparison for X-X Axis b) Comparison for Y-Y Axis

Figure 11. Comparison of Performance Based Analysis Methods

Table 6.1. Performance based and time history analyses result comparison

	X-X Axis Displacement	Y-Y Axis Displacement	Difference of the methods		Difference from Time History	
			(x-x)	(y-y)	(x-x)	(y-y)
Previous Capacity Spectrum (PCS)	12.2cm	11.8 cm	6.08% more than NCS	9.25% more than NCS	37.08% more than TH	51.28% more than TH
			16.43% less than PDC	4.065% less than PDC		
New Capacity Spectrum (NCS)	11.5 cm	10.8 cm	5.75% Less than NDC	6.90% less than NDC	29% More Than TH	38.4% More than TH
			5.73% less than PCS	8.47% less than PCS		
Previous Displacement Coefficient (PDC)	14.6 cm	12.3 cm	19.67% more than NDC	6.04% more than NDC	64.40% more than TH	57.70% more than TH
			19.67% more than PCS	4.24% more than PCS		
New Displacement Coefficient (NDC)	12.2 cm	11.6 cm	6.08% more than NCS	7.40% more than NCS	37% more than TH	48.7% More Than TH
			16.44% less than PDC	5.70% less than PDC		
Time History (TH)	8.9 cm	7.8 cm				

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