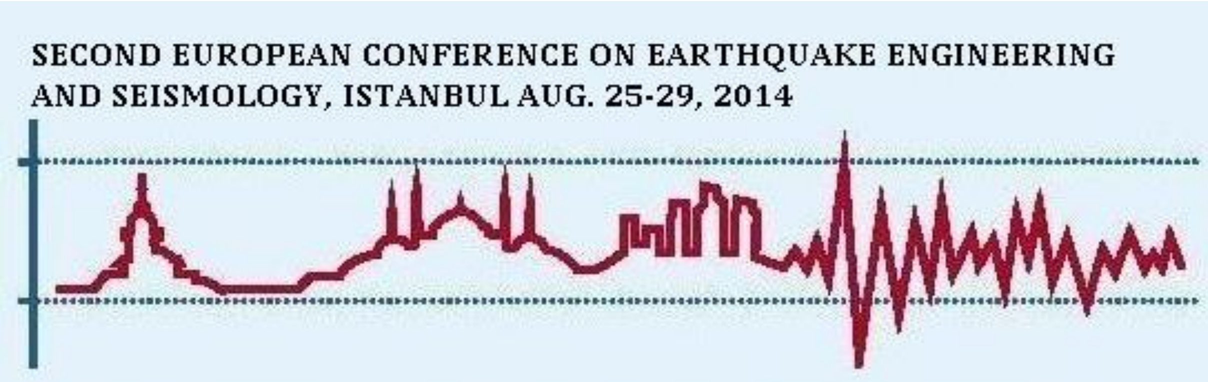

THE DESIGN OF A SCHOOL BUILDING AND COMPARISON OF TARGET DISPLACEMENTS OBTAINED FROM VARIOUS DOCUMENTS

Alperen TÜRKAY[1] and Kadir GÜLER[2]

ABSTRACT

In this study, a school building having four storey which has reinforced concrete frame and shear wall structural system has been designed according to Turkish Earthquake Resistant Design Code 2007 (TERDC-2007) assuming that it will be built in the most active earthquake region of Turkey. The storey area is 450m^2, story height is 3.4m and the material classes for concrete and reinforcement are assumed to be C25 and S420, respectively. The earthquake performance of the structural system of the building has been carried out by using incremental equivalent seismic load method given in TERDC-2007. Furthermore, the target displacement of the building is studied by using documents of Seismic Evaluation and Retrofit of Concrete Buildings (ATC40), Prestandart and Commentary for the Seismic Rehabilitation of Buildings (FEMA 356) and Improvement of Nonlinear Static Seismic Analysis Procedures (FEMA440). The performance of the building has been evaluated under the design earthquake (the probability of exceedence of the design earthquake within a period of 50 years is %10). 3D model of the structural system of the building is used in numerical solutions. The analysis of the structural system and the pushover analysis are accomplished by using SAP2000 software (Structural Analysis Program) incorporating inelastic material behavior for concrete and steel. The numerical results are given in tables and graphs. The comparison of the results has shown that the target displacements obtained from various documents are consistent with each other.

INTRODUCTION

Performance based seismic assessment of buildings thrives as an important subject of earthquake engineering. With recent developments in design and assessment methods, performance based design has become important as much as force based design. Performance based design and evaluation concept covers the methods of geometric nonlinearity utilization and ductility capacity of buildings under certain seismic effects based on probability of occurrence considering the design life of the building. The performance based design and evaluation first mentioned in ATC 40 (1996) and FEMA 356 (2000). TERDC-2007 has a new chapter on performance based evaluation of existing buildings.

The linear elastic and nonlinear elastic behavior approaches are given for performance based assessment in some documents and related codes. In the linear methods, the adequacy of strength of cross sections is examined with regard to the results of the analysis on the basis of linear elastic behavior. In the case of nonlinear methods, the elasto-plastic behavior of the structural system is considered. By using the nonlinear analysis methods, the performance assessment of the building is carried out by using sectional strain and plastic hinge rotations depending on the limitations given in

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some codes and recommended documents. The following nonlinear methods are given in TERDC 2007 for performance assessment of existing buildings:

- Incremental equivalent static seismic load method
- Incremental mode superposition method
- Time domain (dynamic) method

In this study, a four story school building has been designed according to the rules given in TERDC-2007. The earthquake performance of the building has been evaluated by using incremental equivalent seismic load method (pushover analysis). In the pushover analysis SAP2000 is used considering non-linear material behaviors of concrete and steel. The non-linear behavior of the structural system is taken into account by assuming plastic deformation concentrated at the ends of the beams and the columns, which are called as plastic hinges. Pushover analysis is carried out by increasing the lateral load (load vector) such that a target displacement at roof level is encountered. Base shear force – roof displacement curve (pushover curve) is converted to modal acceleration – modal displacement curve after pushover analysis. As a result of that procedure, the roof displacement demand is calculated for the desired earthquake direction and the performance levels of the elements are evaluated by comparing the sectional strains with the limiting values given for different performance levels. Furthermore, the target displacement of the structural system is also determined by using ATC40 (Seismic evaluation and retrofit of concrete buildings), FEMA 356 (Pre-standard and commentary for the seismic rehabilitation of buildings) and FEMA440 (Improvement of nonlinear static seismic analysis procedures). Then, the numerical analysis results are given in tables and figures, comparatively.

DESIGN OF A SCHOOL BUILDING

A reinforced concrete school building has been designed according to TERDC-2007 by using the equivalent seismic load method. The structural system consists of two way slabs, beams, columns and shear walls. The regular frame and dual system is established having 5 and 3 spans in x and y directions, respectively. Frame and dual system has been designed having high ductility level. The structural system of the building is 3D modeled by using SAP2000. Some parameters and characteristics of the building can be given as follows:

Story of the building	: 4
Story height	: 3.4 m
Live load participation factor	: 0.6
Effective seismic factor	: $A_0 = 0.4$
Soil type, Z2	: $T_A = 0.15$ s $T_B = 0.40$ s
Concrete / Reinforcement	: C25 (f_{ck} = 25 MPa) / S420 (f_{yk} = 420 MPa)
Building importance factor, I	: 1.4
Slab thickness	: 0.15 m
Beams	: 0.30m/0.60m
Dimensions of the building	: 30 m (x dir.) / 15 m (y dir.)

Structural layout of the building and 3D structural model of the building are given in Figure 1 and Figure 2, respectively.

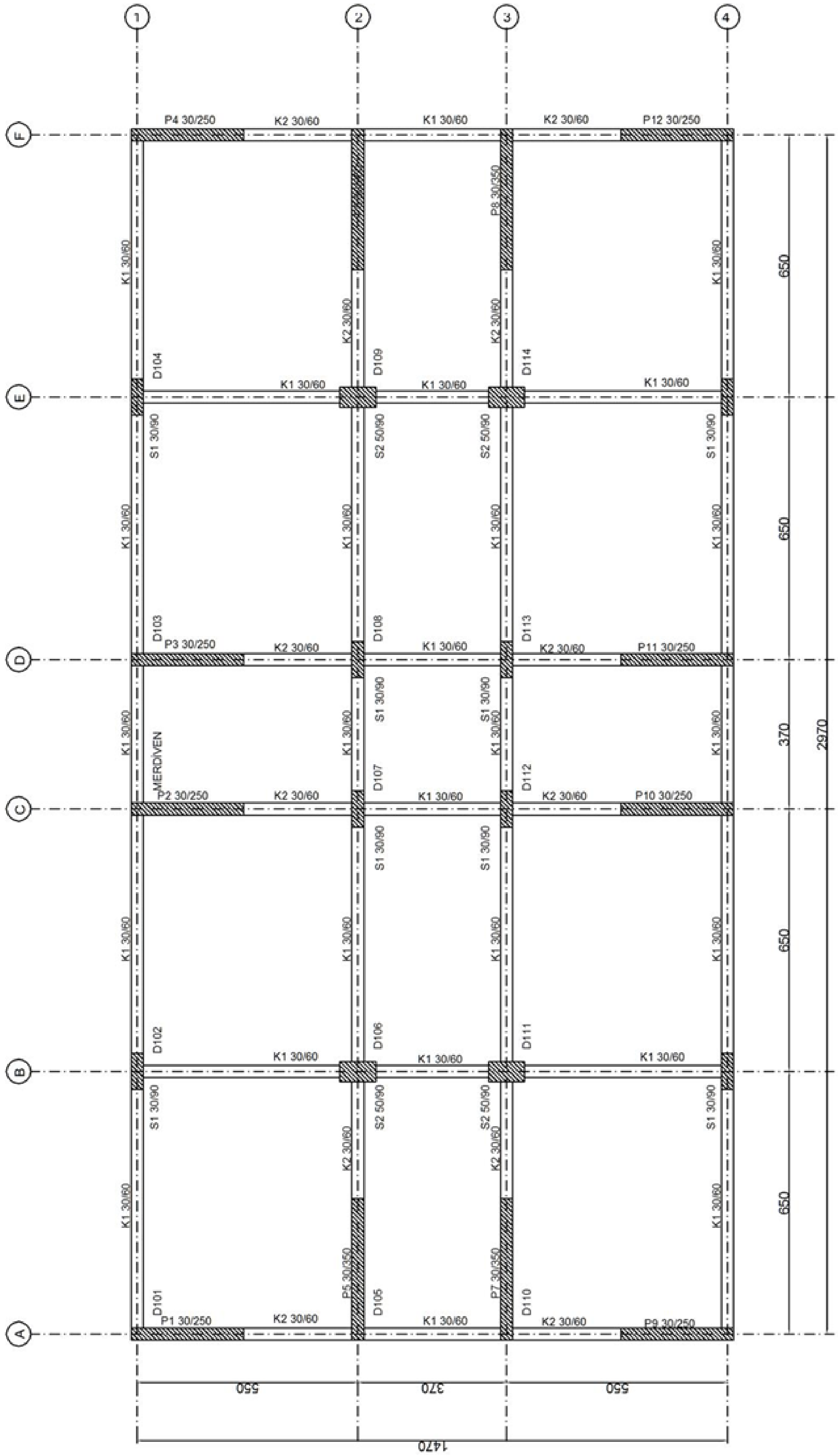

Figure 1. Typical structural layout of the building

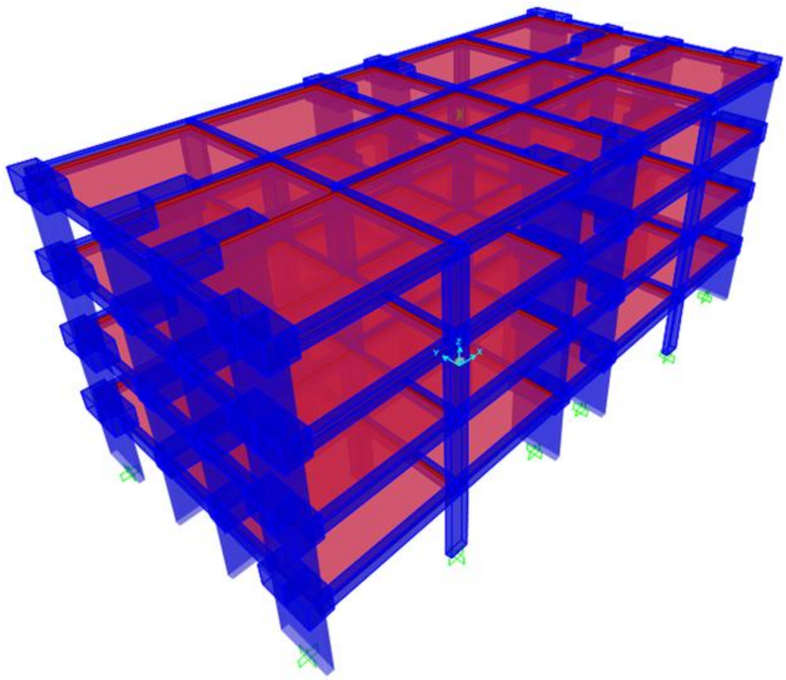

Figure 2. 3D structural model of the building

The beam, column and shear wall sections and reinforcement details are given Figure 3-6.

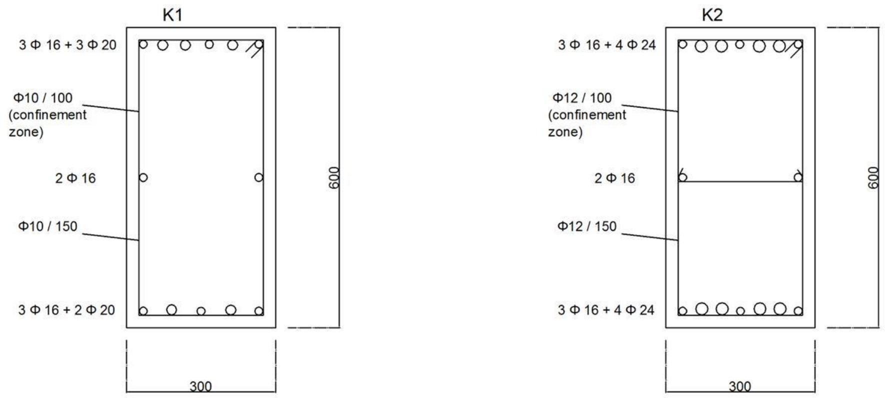

Figure 3. Sections and reinforcement details of the beams

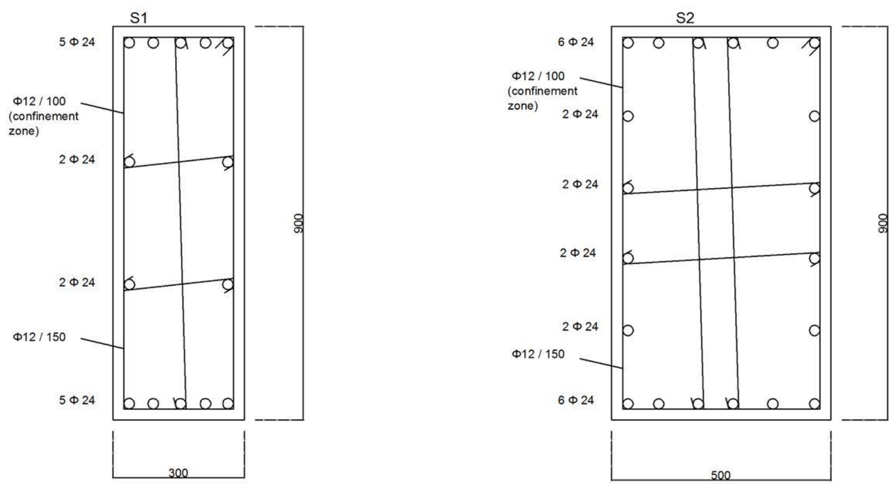

Figure 4. Sections and reinforcement details of columns

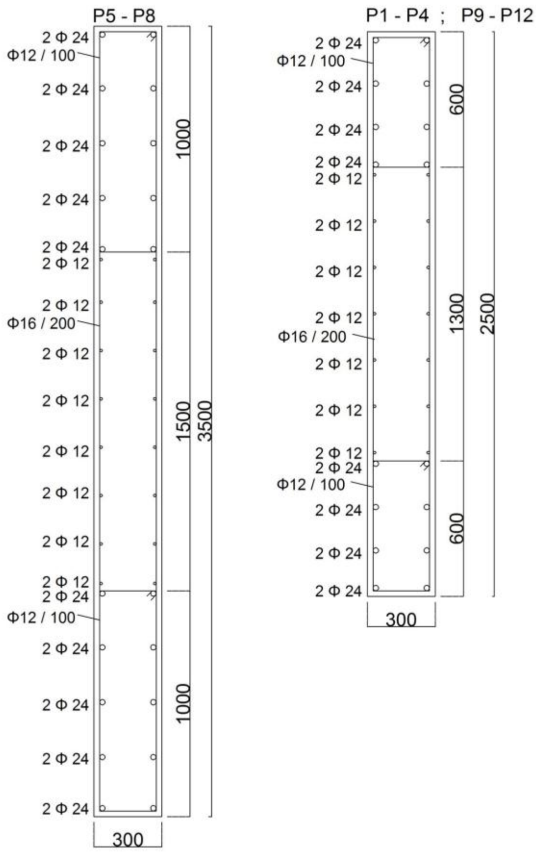

Figure 5. Sections and reinforcement details of shear walls through the critical shear wall height (H_{cr})

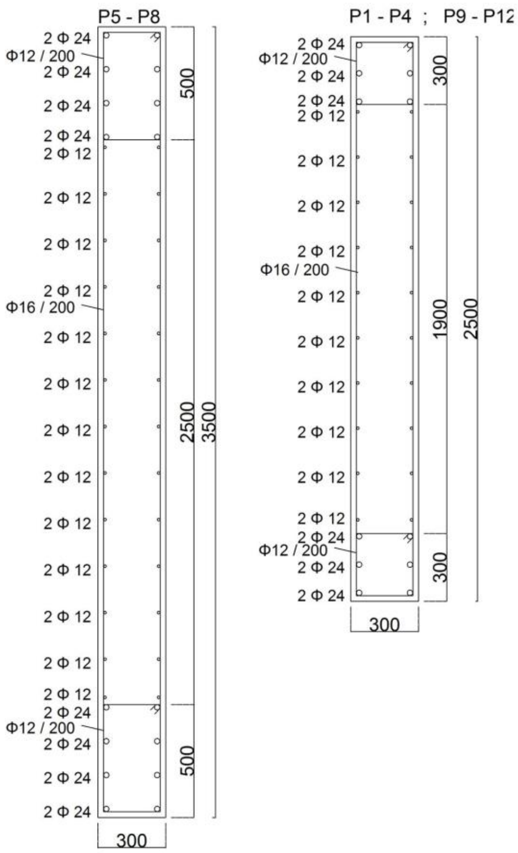

Figure 6. Sections and reinforcement details of shear walls outside of the critical shear wall height (H_{cr})

EARTHQUAKE PERFORMANCE OF THE SCHOOL BUILDING

First two free vibration periods of the buildings are obtained for uncracked and cracked as follows:

Uncracked Y direction T1(y) = 0.3278 s, X direction T1(x) = 0.30686 s
Cracked Y direction T1(y) = 0.47899 s, X direction T1(x) = 0.44542 s

As it is seen, the structural system is more rigid in x direction. The mass participation ratio is equal to %74 and greater than %70 (code limit) for the first mode, torsional irregularity less than 1.4 and number of the story of the building is less than 8, which means that the incremental equivalent seismic load procedure can be used as defined in TERDC-2007.

The concentrated nonlinearity model is implemented in this work by using SAP2000 and 3D structural system. The information level of coefficient is applied as comprehensive (1) as defined in TERDC-2007. Frame and shear wall structural system elements of the building have been defined as frame elements and Mid-Pier frame with plastic hinge in SAP2000. Mid-pier is modeled as a frame element with the shear wall cross sectional parameters (Figure 7), (Fahjan et al., 2011). The plastic P-M-M hinge has been defined with the given rebar distribution for columns and shear walls. The plastic M hinge has been defined with the given rebar distribution for beams.

In the analysis of cross-sections in SAP2000, confined and unconfined Mander concrete models (Mander et al., 1988) and elasto-plastic steel model with hardening were used given in TERDC-2007 (Figure 8).

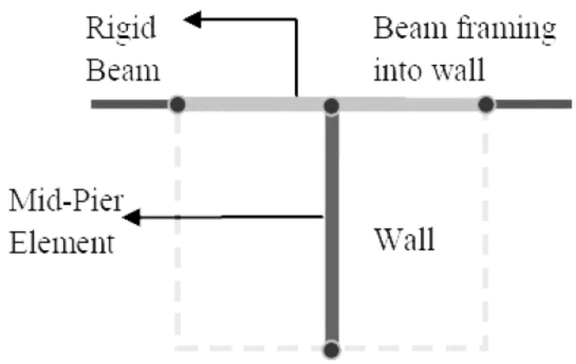

Figure 7. Mid-pier model for shear walls

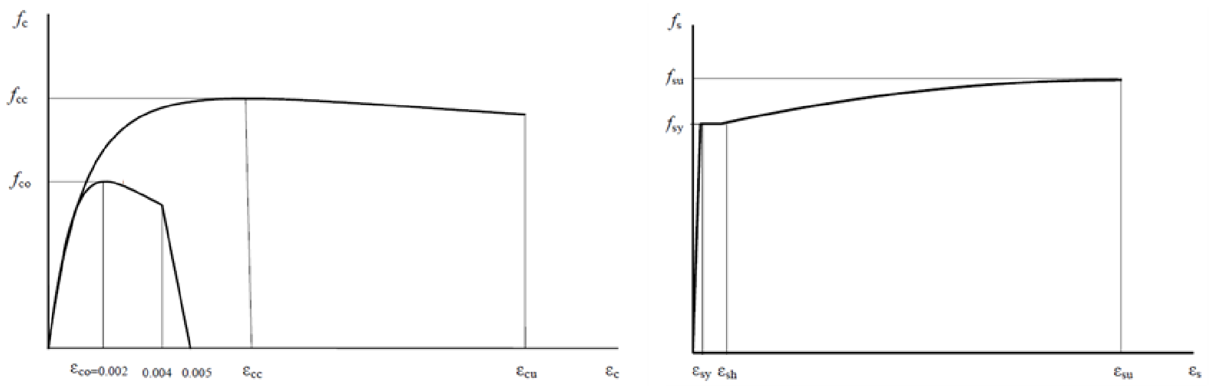

Figure 8. Mander concrete model and reinforcement model used

For pushover analysis, effective bending rigidities $(EI)_e$ of the cracked sections have been used for the reinforced concrete components and these values have been defined for SAP2000 as defined in TERDC-2007.

Load vectors (m_i ϕ_i) used in pushover analysis which is consistent with that of first mode shape are given in Figure 9.

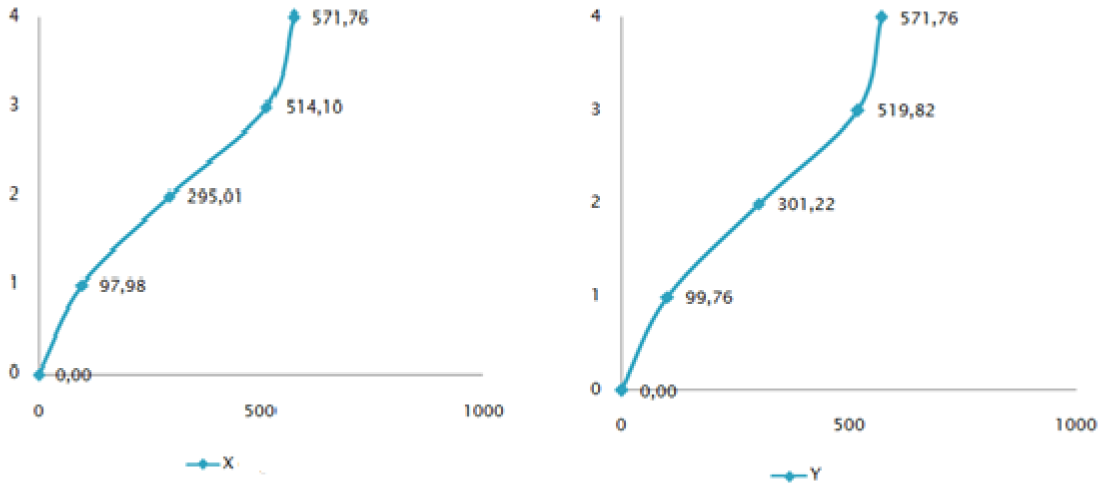

Figure 9. Load vectors for X and Y directions

As a result of the pushover analysis, the base shear force-roof displacement behavior (pushover curve) is obtained (Figure 10) and by coordinate transformation of the pushover curve, the modal acceleration-modal displacement curve (modal pushover curve) is given for Y direction in Figure 11. The nonlinear spectral displacement and roof displacement demand are obtained as follows:

S_{di1} = 0.04936 m (Nonlinear spectral displacement)

U_{YN} = 0.06752 m (Top displacement demand)

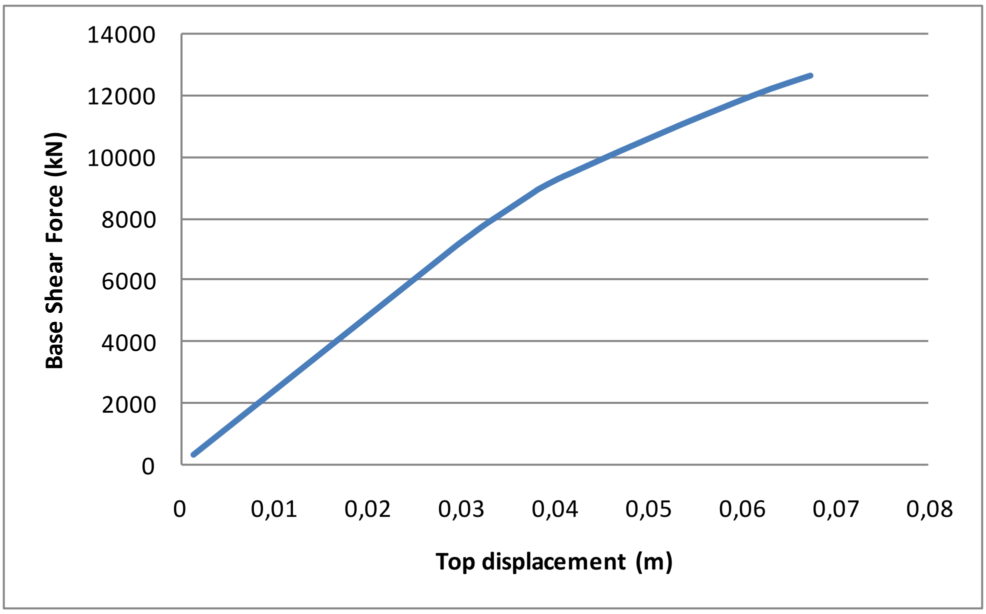

Figure 10. Base shear-roof displacement curve for Y direction

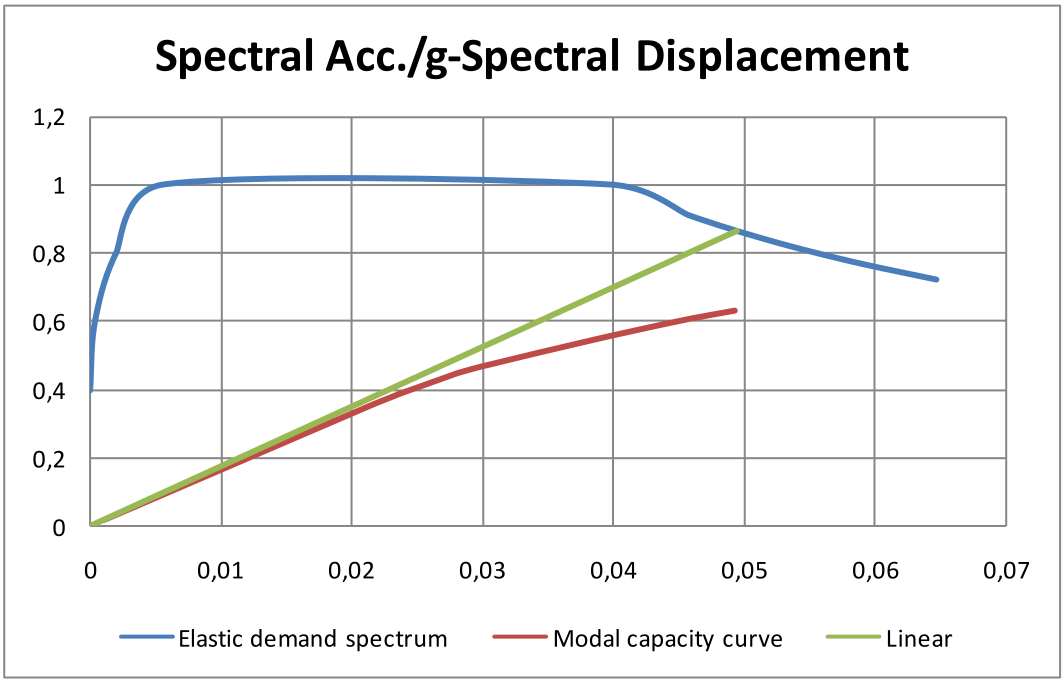

Figure 11. Modal capacity curve for Y direction under design earthquake

Additionally, the target displacement has been determined by using nonlinear static procedures which are coefficient method and capacity spectrum method as defined in FEMA and ATC documents. Horizontal load bearing capacity is related to displacement demand in both documents. The coefficient method uses displacement modification procedures. The target displacement is estimated by modifying the linear elastic displacement of a single degree of freedom system by using several empirical coefficients (Goel, 2011). The target displacement is calculated from Eq. (1) by using coefficient method given in The FEMA356.

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \tag{1}$$

FEMA 440 summaries the results of studies to evaluate the ability of the coefficient method to determine the top displacement of the inelastic structural models (Boroujeni, 2013). Several improvements are presented in FEMA 440 document to the coefficient method in The FEMA 356. FEMA 440 suggests elimination of C_3 coefficient and applies a minimum initial strength requirement for systems (Comartin et al., 2004). Consequently, the target displacement is calculated from Eq. (2) by using coefficient method in The FEMA 440.

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g \tag{2}$$

In capacity spectrum method, the performance point is defined by use of capacity spectrum and reduced demand spectrum. This method tries to identify the performance point coinciding capacity spectrum and reduced demand spectrum.

The target displacement has been calculated by using coefficient method as defined in FEMA356 and FEMA440.

The school building studied, the target displacements (FEMA356) by using related equations and SAP2000 are calculated as follows:

- Using equations : $\delta t = 0.06752$ m (Y direction)
- Using SAP2000 (Figure 12) : D = 0.068 m (Y direction)

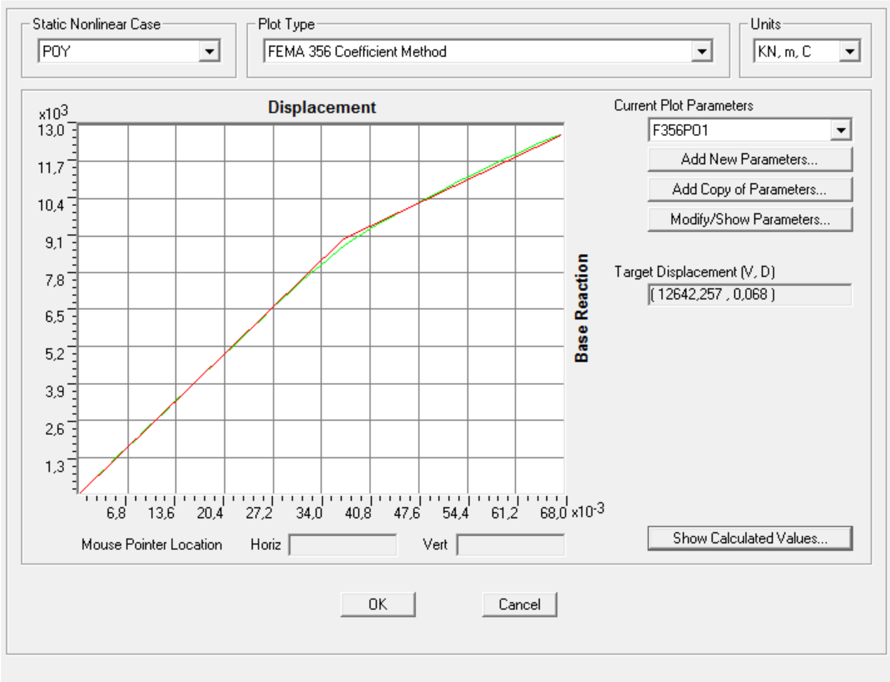

Figure 12. Target displacement in Y direction (SAP2000)

The school building studied, the target displacements (FEMA440) by using related equations and SAP2000 are calculated as follows:

- Using equations : $\delta t = 0.07262$ m (Y direction)
- Using SAP2000 (Figure 13) : D = 0.072 m (Y direction)

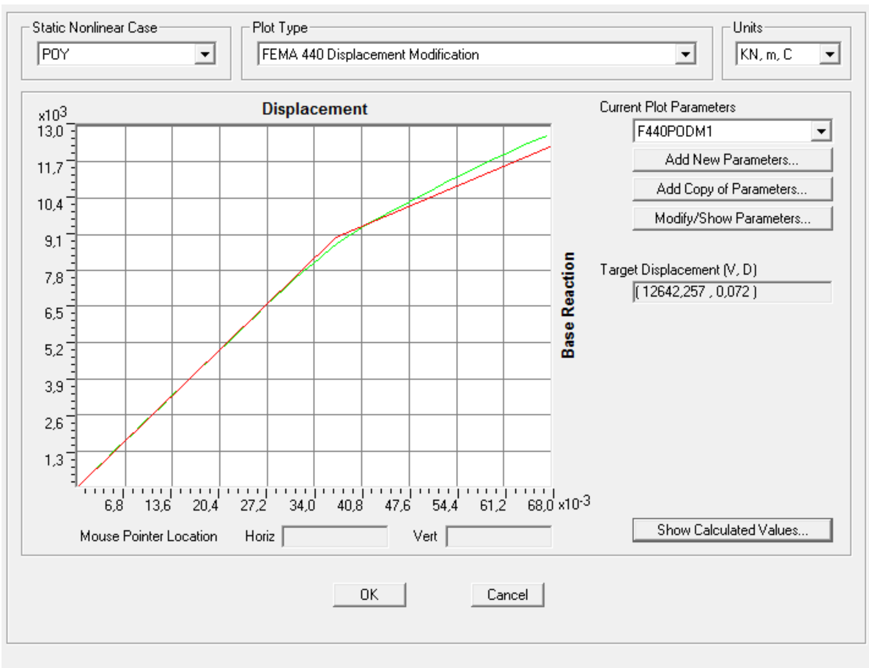

Figure 13. Target displacement in Y direction (SAP2000)

Target displacement has been calculated by using capacity spectrum method as defined in ATC40 and FEMA440. Capacity spectrum method has been carried out by use of SAP2000 (Figure 14-15).

- Target displacement (ATC40) : D = 0.059 (Y direction)
- Target displacement (FEMA440) : D = 0.063 (Y direction)

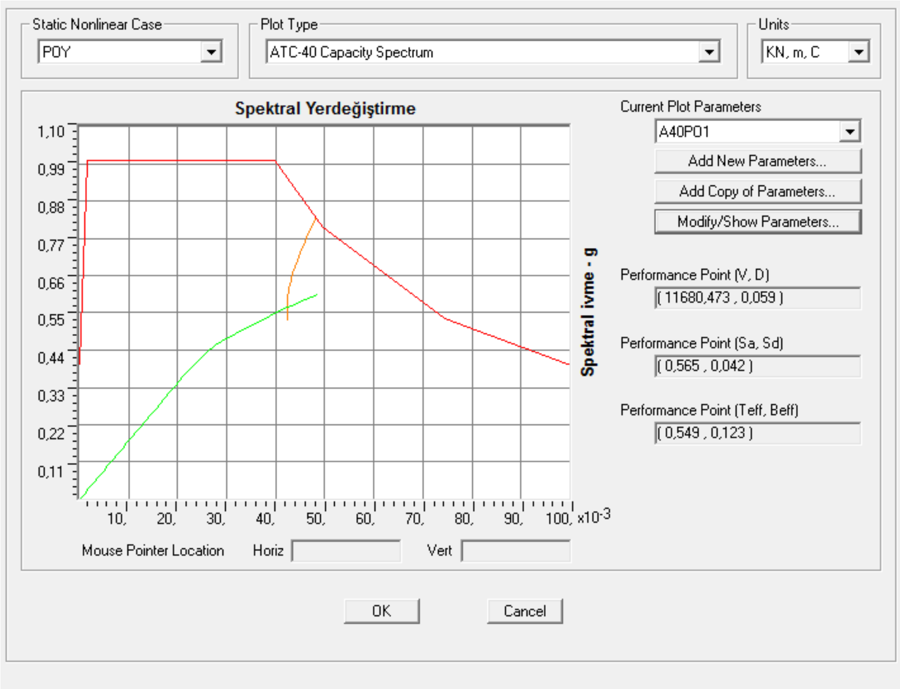

Figure 14. Target displacement in Y direction (SAP2000)

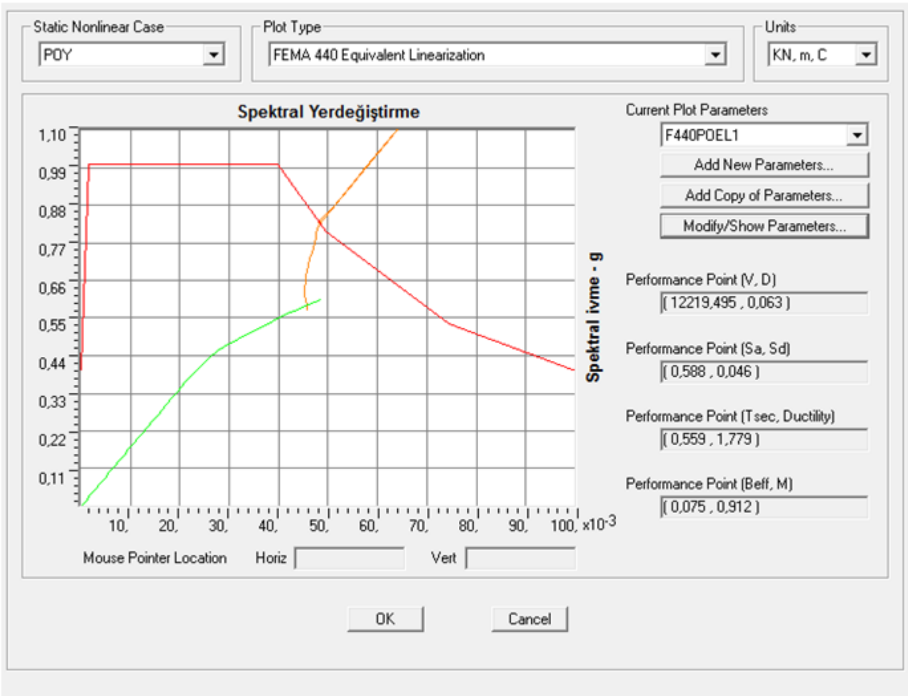

Figure 15. Target displacement in Y direction (SAP2000)

Target displacements obtained from various documents has been given in Figure 16. The results reveal that the target displacement values obtained from various approaches are consistent. ATC40 gives less target displacement.

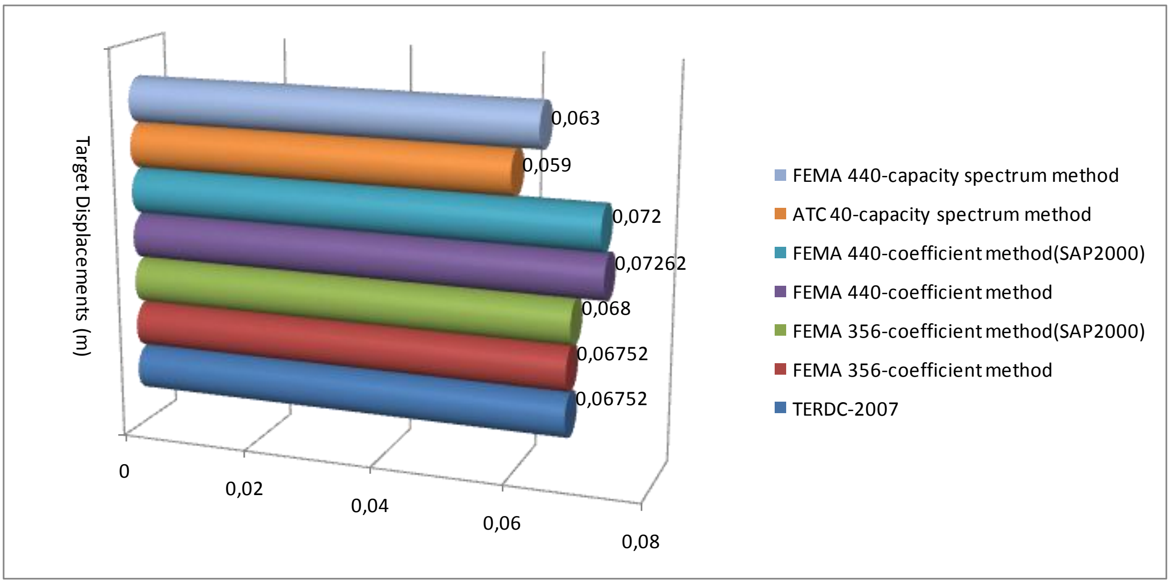

Figure 16. Target displacements

CONCLUSION

A four-story reinforced concrete school building is studied. The structural system of the school building is designed according to TERDC-2007. SAP2000 is used in the numerical analysis of the structural system. The performance assessment of the structural system is carried out by using different related documents. The target displacement of the building has been calculated according to TERDC-2007, ATC40 (capacity spectrum method), FEMA356 (coefficient method), FEMA440 (capacity spectrum method and coefficient method). The following preliminary results can be mentioned:

- The plastic hinge development from static (pushover) analysis shows that results are consistent with that of strong column-weak beam design philosophy.
- The comparison of the results have shown that the target displacements obtained from various approaches, such as documents of (TERDC-2007, FEMA356, ATC40, FEMA440) are consistent with each other.

REFERENCES

Applied Technology Council (1996) ATC-40-Seismic Evaluation and Retrofit of Concrete Buildings, Redwood City, California, ABD

Boroujeni A.R.K (2013) "Evaluation of Various Methods of FEMA 356 Compare to FEMA 440", *Journal of Civil Engineering and Construction Technology*, 4(2): 51-55

Comartin C.D, Aschheim M, Guyader A, Hamburger R, Hanson R, Holmes W, Iwan W, Mahoney M, Miranda E, Moehle J, Rojahn C, Stewart J (2004) "A Summary of FEMA 440: Improvement of Nonlinear Static Seismic Analysis Procedures", *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, 1-6 August

Computers and Structures Inc. (2011) SAP 2000 V15.1- Structural Analysis Program, Berkeley, California, ABD

Fahjan M.Y, Başak K, Kubin J, Tan M.T (2011) "Nonlinear Analysis Methods for Reinforced Concrete Buildings with Shear Walls", *Seventh National Conference on Earthquake Engineering*, Istanbul, Turkey, 30 May-3 June

Federal Emergency Management Agency (2000) FEMA 356-Prestandart and Commentary for the Seismic Rehabilitation of Buildings, Washington, ABD

Federal Emergency Management Agency (2005) FEMA 440- Improvement of Nonlinear Static Seismic Analysis Procedures, Washington, ABD

Goel R.K (2011) “Variability and Accuracy of Target Displacement from Nonlinear Static Procedures”, *International Scholarly Research Network ISRN Civil Engineering*, 10.5402/2011/582426

Mander J.B., Priestly M.J.N. and Park R. (1988) “Theoretical Stress-Strain Model for Confined Concrete”, *Journal of Structural Division ASCE*, 114(8): 1804-1826

Ministry of Public Works and Settlement of Republic of Turkey (2007) Turkish Earthquake Resistant Design Code, Ankara, Turkey

Turkay A (2013) The design of a school building and determination of seismic performance of school building, Postgraduate Thesis, İstanbul Technical University, Turkey