A Comparison Between American and European Codes on the Nonlinear Static Analysis of RC Buildings

C. Bhatt, R. Bento
Instituto Superior Técnico, Lisbon, Portugal

15 WCEE
LISBOA 2012

SUMMARY:

The use of nonlinear static procedures on the seismic assessment of plan irregular buildings has not yet been totally established among the engineering community. The absence of conclusive studies about the application of these methods in such type of buildings limits their use by structural designers. In this paper, the Capacity Spectrum Method (CSM) with the features proposed in the American codes ATC40 and FEMA440, are compared with the Extended version of the N2 method for plan asymmetric buildings (the original version of the N2 is proposed in Eurocode 8). The case study analysed is an existing five storey RC concrete building, and the results are compared with the most exact nonlinear dynamic analysis. Several seismic intensities are tested in order to understand the performance of each method through different levels of structural inelasticity. The results obtained with the extended N2 seem quite optimistic regarding the use of nonlinear static procedures on the seismic assessment of plan asymmetric buildings. However, the American codes procedures evaluated herein need some improvements namely in terms of their ability to reproduce the torsional effects in structures non-regular in plan.

Keywords: Nonlinear seismic response, pushover analysis, nonlinear static procedures, torsion, plan irregular RC buildings

1. INTRODUCTION

Nonlinear Static Procedures (NSPs) can be integrated in a Performance Based Seismic Design philosophy. It is generally recognized that structures designed within these deformation-based criteria, using Performance-Based Design Procedures, are more likely to behave sensibly in seismic scenarios than the structures designed according to the classic force-based philosophy. It is also widely accepted that performance criteria can be better controlled by evaluating the deformations in the structure, both at global and component levels.

Nonlinear Static Procedures are deemed to be very practical tools to assess the nonlinear seismic performance of structures. On the other hand, nonlinear dynamic *time-history* analyses are very time-consuming, which is a relevant drawback in design offices, where the deadlines are restrictive.

The NSPs introduced in this context are a powerful tool for performance evaluation. American seismic design codes, like the FEMA273 (FEMA 1997), FEMA356 (ASCE 2000), FEMA440 (ATC 2005) and the ATC40 (ATC 1996), have recommended the use of this type of procedures. In Europe, Eurocode 8 (CEN 2004) also incorporated the procedure as an evaluation or design technique.

Several scientific studies were developed demonstrating the good performance of some NSPs on the seismic assessment of relatively simple structures such as regular buildings capable of being analysed by planar frames and bridges.

However, the use of such methods to the case of real existing plan irregular structures has so far been studied by a limited number of authors, e.g. Chopra and Goel (2004), Fajfar et al. (2005a) and b) and Bento et al. (2010). This fact limits the application of NSPs to assess current existing structures, the majority of which are irregular in plan. Some issues still need to be clarified regarding the format with which the pushover analysis has to be performed. The positive outcome from recent research seems to indicate that it is certainly worthwhile to continue to pursue the further development and/or verification of NSPs taking a further step with the 3D Pushover problem, with the objective of arriving

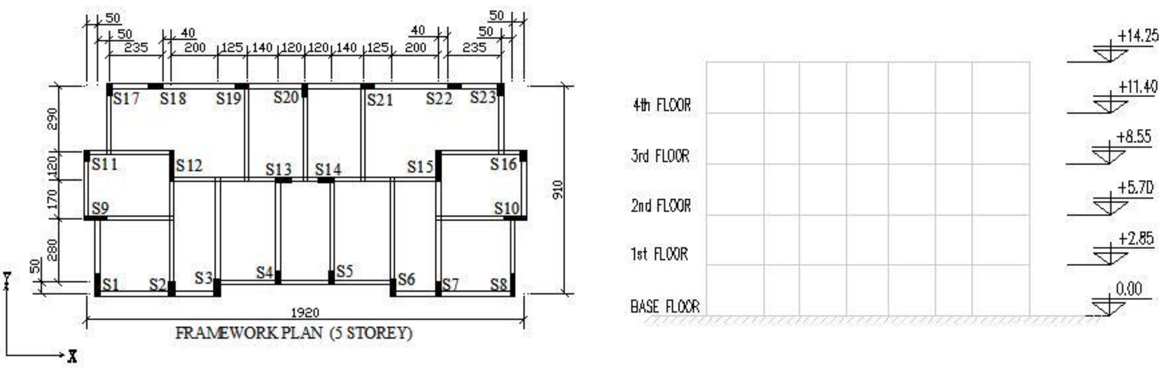
at an eventual introduction in seismic design codes and regulations of improved procedures capable of dealing with plan irregular structures.
In this paper, American and European codes procedures are evaluated and compared: the Capacity Spectrum Method (CSM) (Freeman et al. 1975, Freeman 1998) with the features proposed by ATC40 and FEMA440, and the Extended N2 method for plan asymmetric buildings (Fajfar et al. 2005a) and b).
The case study chosen is an existing Turkish RC five storey building with irregularities in plan. Comparison of the results obtained with nonlinear dynamic analysis, through the use of semi-artificial ground motions, enables the evaluation of the accuracy of the different NSPs.

2. NONLINEAR STATIC PROCEDURES EVALUATED

The nonlinear static procedures were officially introduced in design codes all over the world. They started to be implemented within the framework of performance-based seismic engineering ATC40, FEMA237 and FEMA356. Recently, the Japanese structural design code for buildings (MLIT 2001) has adopted the capacity spectrum method (CSM) of ATC40 as a seismic assessment tool. In Europe, the N2 method (Fajfar and Fischinger 1988, Fajfar 2000) was implemented in Eurocode 8.
The capacity spectrum method, first introduced by Freeman and latter included in ATC40 and in FEMA440, and the N2 method developed by Fajfar and his team and included in Eurocode 8, rely on a pushover analysis using invariant load patterns (the load pattern does not change during the analysis, only the force intensity) to estimate deformation demands under seismic loads. The forces used in the pushover analysis are proportional to the relevant mode of vibration of the structure under analysis (in most of the cases, the first mode is the mode used). The N2 method represents the seismic demand by an inelastic spectrum.
Fajfar et al. proposed in 2005 (a) and b) an extended version of the N2 method for plan asymmetric buildings. In this proposal the pushover analysis of the 3D model is performed independently in each direction, the target displacement being calculated using the original N2 method procedure. In order to take torsional effects into account, the pushover results are amplified by torsional correction factors. These factors are computed through an elastic response spectrum analysis and a pushover analysis. No de-amplification of displacements due to torsion is considered by the method.

3. CASE STUDY

The case study considered in this work is an existing Turkish reinforced concrete 5 storey building. It experienced the 1999 Golcuk earthquake without any damage. The building was designed according to the 1975 Seismic Code of Turkey.



(a) (b)

Figure 1. (a) Plan View (cm), (b) Lateral View (m)

The building is asymmetric in plan along the X axis, Figure 1a), and all the floors have the same height, Figure 1b). There are beams framing into beams leading to possible weak connections in the

structure. There are also walls and elongated columns (wall-like columns), as presented in Figure 1.
The column sections keep the same geometrical and reinforcement features along the height of the building. In columns the stirrups are ø8 with 20cm spacing, constant along the height.
The beam sections are mainly 0.20x0.50m^2 except the two located at the centre of the building that are 0.20x0.60m^2. The stirrups have 20cm spacing both for beams and columns. The slabs are 0.10m and 0.12m thick.
The mass of each story is considered to be 263ton, except in the last storey where the mass is 150ton. For more details on the building's characteristics see Vuran et al. (2008).
In this work, it is assumed that the structure is properly designed for shear, and therefore the collapse of the building is not due to brittle failures.

4. MODELING FEATURES

The structural analysis software used in this study was SeismoStruct (SeismoSoft 2006), a fibre-based structural analysis program. It is able to run eigenvalue analysis, nonlinear static (conventional and adaptive) analysis and nonlinear dynamic analysis. The 3D building was represented with a space frame model assuming the centrelines dimensions. The inelastic behaviour of the structural elements was modelled using a fibre element model, with each fibre being characterised by the material relationships described below.
Hysteretic damping was already implicitly included in the nonlinear fibre model formulation of the inelastic frame elements. It was used a 5% tangent stiffness-proportional damping in order to take into account for possible non-hysteretic sources of damping.
The concrete was represented by a uniaxial model that follows the constitutive relationship proposed by Mander et al. (1988) and the cyclic rules proposed by Martinez-Rueda and Elnashai (1997). The confinement effects provided by the lateral transverse reinforcement are incorporated through the rules proposed by Mander et al. (1988) whereby constant confining pressure is assumed throughout the entire stress-strain range. A compressive strength of 16.7MPa was considered.
The constitutive model used for the steel was the one proposed by Menegotto and Pinto (1973) coupled with the isotropic hardening rules proposed by Filippou et al. (1983). Average yield strength of 371MPa was assumed.
The rigid diaphragm effect was modelled using the Nodal Constraints Rigid Diaphragm with Penalty Functions option. The penalty function exponent used was 10^7.
Since there were no available data about the material properties of the analysed buildings, the average values used were based on extensive laboratory tests on core samples collected from Istanbul and around (Bal et al. 2008), where the buildings are located. These values represent the material properties of the existing building stock in the northern Marmara region.

5. SEISMIC ASSESSMENT

In this section the parametric study is described, as well as the seismic action definition and the structural analyses performed.

5.1. Seismic Action

In this study, three bi-directional semi-artificial ground motion records were considered. The three real records taken from the PEER's database website (PEER 2009) are presented in Table 1.
The records were fitted to the Eurocode 8 elastic design spectrum (with the Turkish code features – Type 1 soil A) using the software RSPMatch2005 (Hancock et al. 2006). The ground motions were scaled for several intensity levels of peak ground accelerations.

For the NSPs the response spectra used are the median of the response spectra defined, compatible with the considered accelerograms (Figure 2).

Table 1. Records used in this study

Earthquake Name	YEAR	ClstD (km)	Earthquake Magnitude	Site Classification Campbell's geocode	Mechanism Based on Rake Angle
Tabas, Iran	1978	13.94	7.35	Firm Rock	Reverse
Whittier Narrows-01	1987	40.61	5.99	Very Firm Soil	Reverse - Oblique
Northridge-01	1994	37.19	6.69	Firm Rock	Reverse

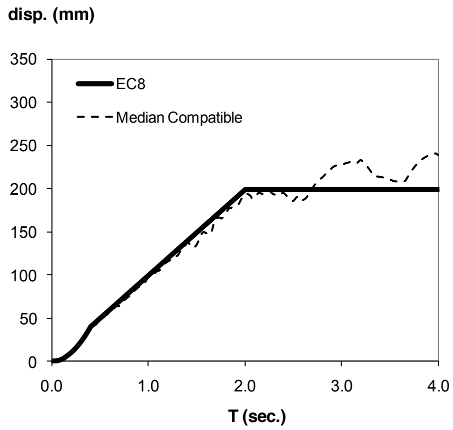


Figure 2. Displacement response spectra, 0.4g

5.2. Structural analyses

Conventional force pushover analyses were carried out in this study. For the N2 method, two load patterns - mass-proportional and modal-proportional - were applied in the structure. For the CSM, only modal-proportional load patterns were applied, as prescribed in the respective codes. In both cases, the force/displacement loads were applied independently in the two horizontal positive/negative directions. For each of the resulting eight loading cases, the target displacement was evaluated with the larger value in each direction being chosen.

For the nonlinear dynamic analysis, the aforementioned three bidirectional semi-artificial ground motion records were used. Each record was applied twice in the structure changing the direction of the components, resulting in 6 runs for each seismic intensity: 0.1, 0.2, 0.4, 0.6 and 0.8g.

6. ANALYSES RESULTS

In this section, the results obtained with the analysed methods are compared with the non-linear dynamic *time-history* analyses for different levels of seismic intensity.

The roof displacements determined from different NSPs were normalized by the corresponding median responses of nonlinear dynamic analysis, as shown in Eq. 6.1, which give an estimate of bias − how good or bad is the NSP under scrutiny for predicting that particular response − as the target reference value in ideal condition should simply be unity. An NSP is said to be biased towards underestimating the response if normalized response is less than one and overestimating the same if the ratio exceeds one. This provides a point of comparison among different NSPs. Ideally one would desire such ratios to tend to unity, which means the NSPs would perfectly match the *time-history* median results. Figure 3 illustrates the top displacement ratios in the centre of mass in both X and Y directions.

$$Top\ Displacement\ ratio = \frac{NSP's\ top\ displacement}{Time\ history\ median\ top\ displacement} \tag{6.1}$$

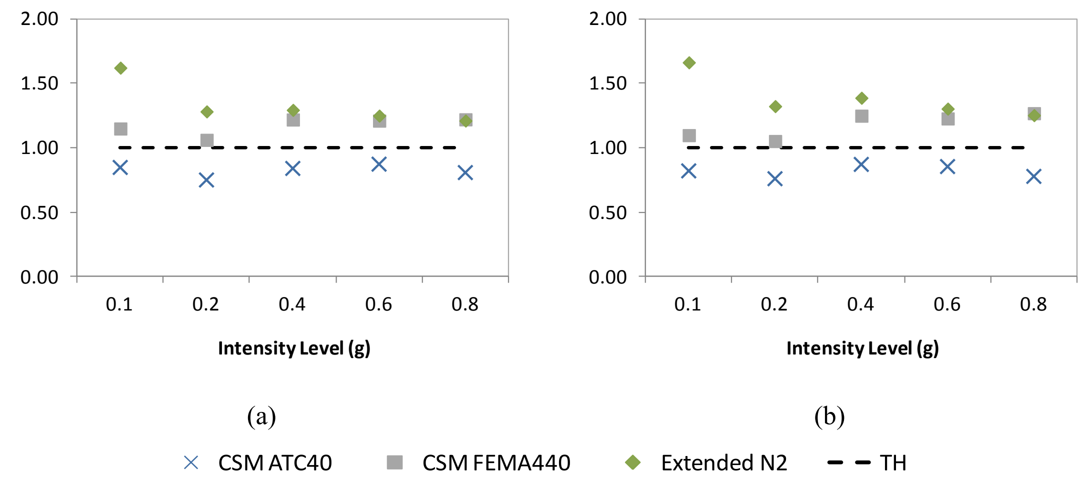


Figure 3. Top displacement ratios, centre of mass a) X direction, b) Y direction

In the elastic or almost elastic range (0.1g and 0.2g) the CSM-FEMA440 leads to estimations very close to the *time-history* in both directions, while the extended N2 overestimates the top displacements in this stage.
In the inelastic regime (0.4g to 0.8g) the CSM-FEMA440 and the Extended N2 lead to approximately same predictions and always conservative.
The CSM-ATC40 underestimates the results for all the seismic intensities in both directions.
The comparison of the different NSPs and the nonlinear dynamic median results in terms of lateral displacement profiles are plotted in Figure 4.

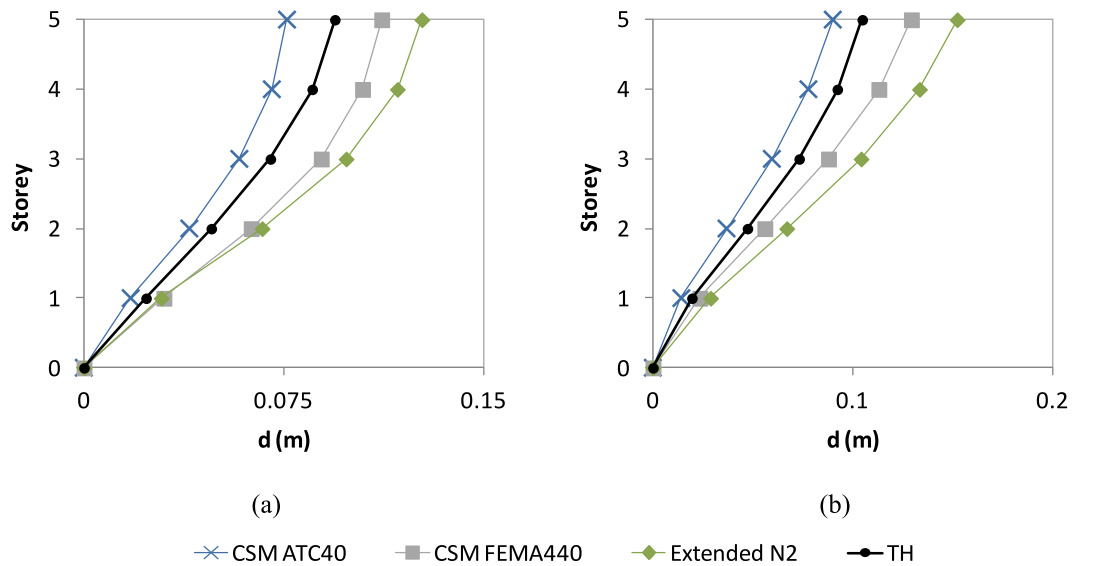


Figure 4. Lateral displacement profiles, 0.4g: a) column S23, X direction, b) column S1, Y direction

Figure 4 shows that the CSM-FEMA440 and the Extended N2 method lead to overestimated predictions of lateral displacement profiles, while the CSM-ATC40 underestimates the results.
Interstorey drifts and chord rotation profiles are represented in Figure 5.

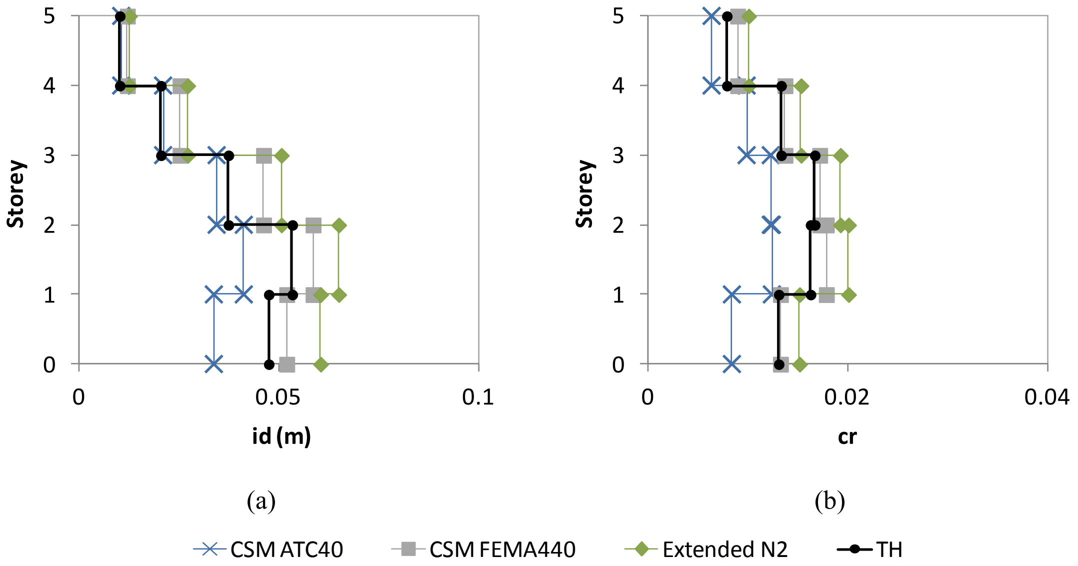


Figure 5. a) Interstorey drifts, column S1, X direction, 0.6g, b) Chord rotations, column S23, Y direction, 0.6g

In terms of interstorey drifts and chord rotation profiles one can observe that the CSM-FEMA440 and the Extended N2 method lead to pretty similar results and both very close to the *time-history* median response, but always conservative. The CSM-ATC40 underestimates the interstorey drifts in the first three storeys and estimates them in an accurate fashion in the upper floors. This method underestimates the chord rotation profiles in all the floors.

From the presented results one can conclude that the Extended N2 method and the CSM-FEMA440 lead to overestimated results when compared with the *time-history* analyses for all the seismic intensities analysed, but usually close to the *time-history* median response.

The CSM-FEMA440, usually led to results closer to the *time-history*, mainly due to the innovative and powerful algorithm proposed by FEMA440 for the target displacement calculation (Bhatt and Bento 2011).

The CSM-ATC40 usually leads to underestimated results for all seismic intensities. This happens because the formulas to compute the equivalent damping proposed by ATC40, used for the spectral reduction factor to calculate the target displacement, overestimate the real value. This is explained in Bhatt and Bento (2011).

The pattern of roof displacements in plan, normalized by the same at centre of mass, as shown in Figure 6, gives an idea how torsional rotation changes the displacement demands at the edges.

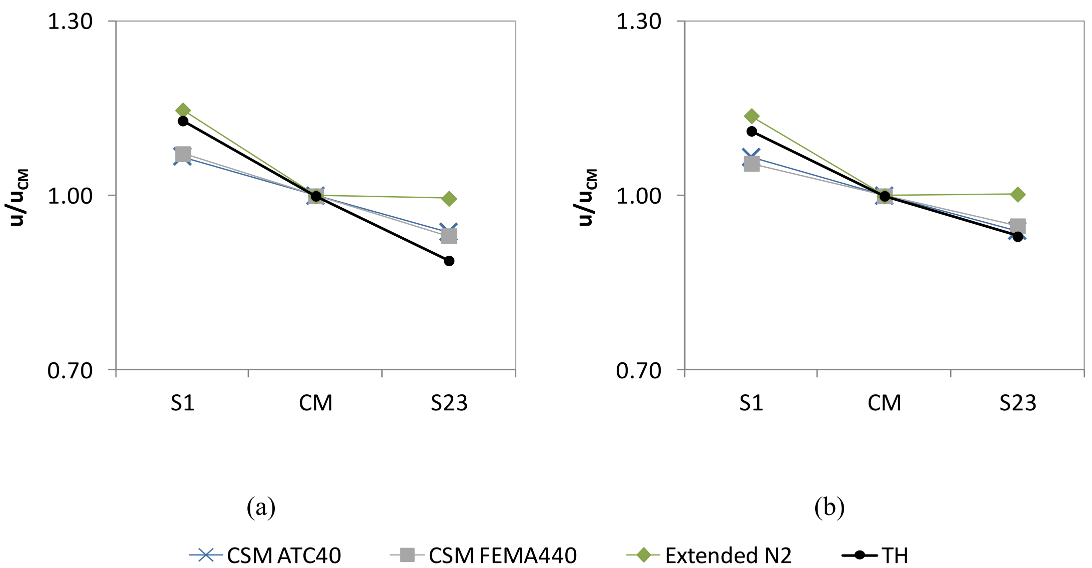


Figure 6. Normalized roof displacements, X direction: a) 0.2g, b) 0.6g

Analysing the normalized roof displacements in Figure 6, it is clear that the extended N2 was the method that better reproduced the torsional motion of the building in the X direction (the asymmetric direction of the structure). In fact, the method captures in a very accurate fashion the torsional amplification on the flexible edge of the building, column S1, for 0.2g and 0.6g. The extended N2 method led to conservative results on the stiff side of the building, column S23, through all the seismic intensities, because it does not consider any de-amplification effect due to torsion.

The CSM-FEMA440 and the CSM-ATC40 always predicted the torsional motion of the building in a linear way from one side of the building to the other, usually underestimating the torsional amplification on the flexible side and overestimating the response on the stiff edge. Therefore, these methods need some improvements in order to correctly reproduce the torsional motion of plan irregular buildings.

7. CONCLUSIONS

In this paper, two American codes NSPs – CSM-ATC40 and CSM-FEMA440 – and the extension of the N2 method (the original version is prescribed in Eurocode 8) for plan asymmetric buildings are evaluated and compared in an existing Turkish RC five storey building.

The results obtained in this study, in terms of top displacements, lateral displacement profiles, interstorey drifts and chord rotations, showed that the CSM-FEMA440 and the Extended N2 are the methods that better reproduced the nonlinear dynamic median response profiles, although the CSM-FEMA440 was usually closer to the *time-history*. Both methods always led to conservative estimations of the structural response.

The good performance of the CSM-FEMA440 can be explained due to its accurate procedure to calculate the target displacement proposed in FEMA440, which includes: a new and efficient algorithm to compute the effective period and the effective damping; an accurate demand spectrum reduction factor coupled with the new concept of modified acceleration-displacement response spectrum (MADRS).

The CSM-ATC40 usually underestimated the response of the building, mainly because the formulas proposed by this code overestimate the equivalent damping for the spectral reduction factor calculation.

In terms of normalized top displacements, the extended N2 method was the only method that reproduced in a correct fashion the torsional motion of the building for different levels of seismic intensity. This good performance can be justified by the fact that such method uses correction factors based on an elastic response spectrum analysis, without considering any de-amplification of displacements due to torsion. Therefore the method is able to capture the torsional amplification on the flexible edge of the building, and it generally leads to conservative results on the stiff side. CSM-ATC40 and CSM-FEMA440 generally reproduced in a linear way the torsional motion from one side of the building to the other. For each intensity level in each direction, these methods were only able to capture the torsional behaviour of just one side of the building, under predicting the other. Therefore, both American codes prescribed methods – CSM-ATC40 and CSM-FEMA440 – need improvements in order to correctly estimate the torsional motion of plan asymmetric buildings.

Further work considering other buildings with different typologies should be carried out in order to reach definitive conclusions.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Ihsan Bal for providing valuable data related to the five storey building. A special acknowledgment to Dr. Rui Pinho for the valuable discussions that certainly enriched the work herein presented. The authors would like to acknowledge the financial support of the Portuguese Foundation for Science and Technology (Ministry of Science and Technology of the Republic of Portugal) through the research project PTDC/ECM/100299/2008 and through the PhD scholarship SFRH/BD/28447/2006 granted to Carlos Bhatt.

REFERENCES

ASCE, American Society of civil Engineers. (2000). Prestandard and commentary for the seismic rehabilitation of buildings, FEMA-356. Washington D.C.

ATC, Applied Technology Council. (1996). Seismic Evaluation and Retrofit of Concrete Buildings, vol. 1 and 2, Report No. ATC-40. Redwood City, CA.

ATC, Applied Technology Council. (2005). Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA440 Report. Redwood City, CA.

Bal, I, Crowley, H., Pinho, R and Gulay, G. (2008). Detailed assessment of structural characteristics of Turkish RC building stock for loss assessment models. *Soil Dynamics and Earthquake Engineering*. **28**, 914-932.

Bento, R., Bhatt, C., Pinho, R. (2010). Using Nonlinear Static Procedures for Seismic Assessment of the 3D Irregular SPEAR Building. *Earthquakes and Structures*. **1:2**, 177-195.

Bhatt, C., Bento, R. (2011). Extension of the CSM-FEMA440 to Plan-Asymmetric Real Building Structures. *Earthquake Engineering and Structural Dynamics*. **40:11**, 1263-1282.

CEN, Comité Européen de Normalisation. (2004). Eurocode 8: Design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings. EN 1998-1:2004. Brussels, Belgium.

Chopra, A.K., Goel, R.K. (2004). A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. *Earthquake Engineering and Structural Dynamics*. **33**, 903-927.

Fajfar P., Fischinger M. (1988). N2 - A method for non-linear seismic analysis of regular buildings. *Proceedings of the Ninth World Conference in Earthquake Engineering*. 111-116. Tokyo-Kyoto, Japan.

Fajfar, P., Marušic, D., Perus, I. (2005a). The extension of the N2 method to asymmetric buildings. *Proceedings of the 4th European workshop on the seismic behaviour of irregular and complex structures*. Thessaloniki.

Fajfar, P., Marusic, D., Perus, I. (2005b). Torsional effects in the pushover-based seismic analysis of buildings. *Journal of Earthquake Engineering*. **9:6**, 831-854.

Fajfar. (2000). A nonlinear analysis method for performance-based seismic design. *Earthquake Spectra*. **16:3**, 573-592.

FEMA, Federal Emergency Management Agency. (1997). NEHRP guidelines for the seismic rehabilitation of buildings (FEMA 273). Washington D.C.

Filippou, F.C., Popov, E.P., Bertero, V.V. (1983). Modelling of R/C joints under cyclic excitations. *Journal of Structural Engineering*. **109:11**, 2666-2684.

Freeman S.A., Nicoletti J.P., Tyrell J.V. (1975). Evaluation of existing buildings for seismic risk - A case study of Puget Sound Naval Shipyard, Bremerton, Washington. *Proceedings of U.S. National Conference on Earthquake Engineering*. 113-122. Berkeley, USA.

Freeman. (1998). Development and use of capacity spectrum method. *Proceedings of the Sixth U.S. National Conf. Earthquake Engineering*. Seattle, Oakland, USA.

Hancock, J., Watson-Lamprey, J., Abrahamson, N.A., Bommer, J.J., Markatis, A., McCoy, E., Mendis, R. (2006). An improved method of matching response spectra of recorded earthquake ground motion using wavelets. *Journal of Earthquake Engineering*. **10:S1**, 67-89.

Mander, J.B., Priestley, M.J.N., Park, R. (1988). Theoretical stress-strain model for confined concrete. *ASCE Journal of Structural Engineering*. **114:8**, 1804-1826.

Martinez-Rueda, J.E., Elnashai, A.S. (1997). Confined concrete model under cyclic load. *Materials and Structures*. **30:197**, 139-147.

Menegotto, M., Pinto, P.E. (1973). Method of analysis for cyclically loaded RC plane frames including changes in geometry and non-elastic behaviour of elements under combined normal force and bending. *Symposium on the Resistance and Ultimate Deformability of Structures anted on by well defined loads, International Association for Bridges and Structural Engineering*. 15-22. Zurich, Switzerland.

MLIT, Ministry of Land Infrastructure and Transport. (2001). Design example and commentary for the calculation of response and limit strength (in Japanese). Japan.

PEER. Strong Ground Motion Database, Available from: http://peer.berkeley.edu/nga/. 2009.

Seismosoft. (2006). Seismostruct - A computer program for static and dynamic nonlinear analysis of framed structures. Available online from URL: www.seismosoft.com.

Vuran, E., Bal, Y.E., Crowley, H., Pinho, R. (2008). Determination of equivalent SDOF characteristics of 3D dual structures. *Proceedings of the 14th World Conference on Earthquake Engineering*. S15-031. Beijing, China.