Verification of Nonlinear Static Procedures for a 3D Plan-Irregular Building in Turkey

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ABSTRACT
The performance of Nonlinear Static Procedures (NSPs) as a tool for the seismic assessment of plan-regular buildings, which can be analysed by means of planar 2D frame models, is supported by many extensive studies. The demand of these methods has been increasing because they represent a good relation between time consuming and accuracy when performing nonlinear analyses. However, the use of NSPs when dealing with 3D irregular structures has been tested by very few studies. Since the majority of real structures are irregular in plan, the use of these procedures is not widespread yet. In this study four commonly employed nonlinear static procedures (CSM, N2, MPA, ACSM) are applied in the assessment of an irregular 3D building - a real Turkish 8 storey RC building with irregularities in plan. The accuracy of different NSP is evaluated by comparing its results with nonlinear dynamic analysis in terms of interstorey drifts, normalized top displacements, lateral displacement patterns, chord rotations and top displacements' ratios. A special attention will be given to the ACSM (Adaptive Capacity Spectrum Method) which performance in 3D plan-irregular buildings is recently being tested.

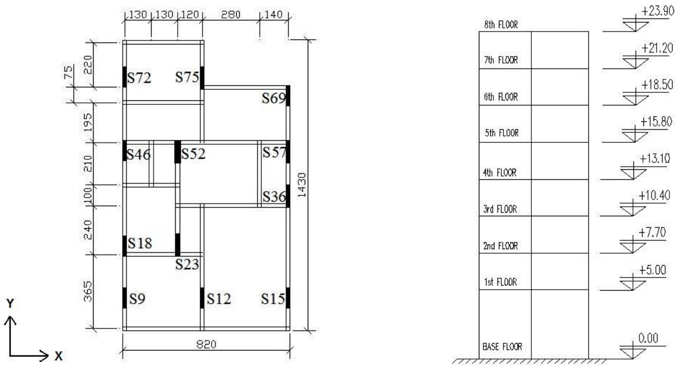
Keywords: Seismic assessment, Real 3D irregular buildings, Nonlinear Static Procedures

1. INTRODUCTION

Although the majority of real structures are irregular in plan, only very few studies have been focused on the NSPs performance for these cases, such as (Chopra and Goel 2004; Fajfar et al. 2005; Bento et al. 2010). Therefore, the use of these methods in these kinds of structures is still limited. On the other hand, the few available studies end up by analyzing only one single NSP procedure. This fact does not allow a useful comparison between several available methodologies.
Therefore, in this work four commonly employed nonlinear static procedures (CSM – Capacity Spectrum Method, N2, MPA – Modal Pushover Analysis, ACSM – Adaptive Capacity Spectrum Method) are applied in the seismic assessment of a real Turkish 8 storey RC building. Comparison with the results obtained with nonlinear dynamic analysis enables the evaluation of the accuracy of the different NSPs.

2. CASE STUDY

The case study selected for this work is a real Turkish reinforced concrete 8 storey building. It is a plan-irregular structure since it is asymmetric along the X and Y axis, Fig. 2.1a). The first storey height amounts to 5.00m and the other floors have the same 2.70m height, Fig. 2.1b). There are beams framing into beams leading to possible weak connections in the structure. There are also walls and elongated columns, as presented in Fig. 1a), with the higher dimension always along the Y direction. For this reason, the structure will be more stiff and resistant along the Y direction.
The columns sections and reinforcement are presented in Fig. 2.2. They keep the same geometrical features along the height of the building, except the column S52 that varies from 1.1x0.3m^2 (on the first floor) to 0.8x0.3m^2 (on the last floor). The height of this section is reduced in 0.1m at every two storeys.
The beam sections are mainly 0.20x0.50m^2 except the two located in the centre of the building along the X direction that are 0.30x0.50m^2 and 0.25x0.50m^2 respectively. The slabs are 0.12m thick.



(a) (b)

Figure 2.1. (a) Plan View (cm), (b) Lateral View (m)

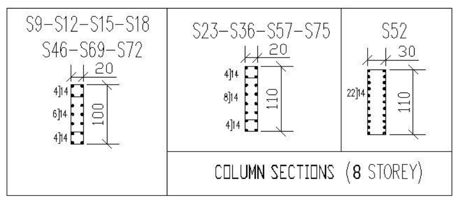


Figure 2.2. Column sections (cm) and reinforcement (mm)

3. MODELLING ISSUES

The structural analysis software used in this study was SeismoStruct (SeismoSoft 2006), a freely downloadable fibre-based structural analysis program. It is capable of predicting the large displacement behaviour of space frames under static or dynamic loading, taking into account the inelastic behaviour of the materials as well as the geometric nonlinearities of the elements.

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 16.7 MPa 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 371 MPa 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.

In this work, 7 controlled nodes were chosen to evaluate the NSPs' performance: the columns S9, S69, S15, S72, S23, S52 (Fig. 2.1a) and the centre of mass (CM).

4. SEISMIC ASSESSMENT – NUMERICAL STUDY DESCRIPTION

4.1. Seismic Action

In this study, three bi-directional semi-artificial ground motion records were considered. These three are real records (Table 4.1) taken from the PEER's database website (PEER 2009).

Table 4.1. 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

The records were fitted to the Eurocode 8 (CEN 2004) 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 intensity levels of peak ground accelerations of 0.1, 0.2 and 0.4g.
For the NSPs the response spectra used are the median of the response spectra defined, compatible with the accelerograms adopted (Fig. 4.1).

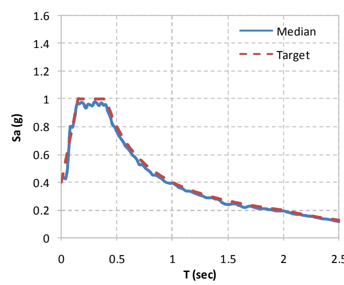


Figure 4.1. Response Spectrum, 0.4g

4.2. Considered Nonlinear Static Procedures

The NSPs herein scrutinised may be split into two main groups.
The first set of NSPs comprises the pioneering Capacity Spectrum Method (CSM), introduced by Freeman and collaborators (Freeman et al. 1975; Freeman 1998) and implemented in ATC-40 guidelines (ATC 1996), and the equally innovative N2 method suggested by Fajfar and co-workers (Fajfar and Fishinger 1988, Fajfar 2000) and later included in Eurocode 8 (CEN 2004). These first proposals are characterised by their simplicity and usually consider a first mode and/or uniform load distributions in the computation of the pushover/capacity curve. Each one of these two approaches was considered in two modalities; N2/Extended N2 and CSM-ATC40/CSM-FEMA440. The Extended N2 method (Fajfar et al. 2005) consists of an extension to the 3D space of the original N2 method, whilst the CSM-FEMA440 variant features the improved MDOF-to-SDOF transformation rules given in the FEMA-440 report (ATC 2005).
The second group features the more recent proposals of Chopra and Goel (Chopra and Goel 2002 and 2004) on a Modal Pushover Analysis (MPA) and of Casarotti and Pinho (2007) by means of Adaptive Capacity Spectrum Method (ACSM). All of them present improvements with respect to their predecessors, such as the inclusion of higher modes contribution, the consideration of progressive damage, and alternative definitions of reference node; the latter can result very opportune in 3D analysis.

4.3. Structural Analyses Carried Out

Two types of pushover analyses were carried out: the so-called conventional force pushover and the Displacement-based Adaptive (DAP) pushover algorithm (Antoniou and Pinho 2004). For the former, two load patterns - mass-proportional and modal - were applied in the structure. In DAP, the displacements were applied on all mass nodes of the structure and spectral scaling was considered to weigh the contribution of the different modes. 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 employed. Each record was applied twice in the structure changing the direction of the components, resulting in 6 runs of incremental dynamic analyses (0.1g, 0.2g and 0.6g).

The results in terms of top displacements, displacement patterns, interstorey drifts, chord rotations and top rotations in the two directions were calculated and compared for all seismic intensity levels, and for all nonlinear static (N2, Extended N2, MPA, CSM-ATC40, CSM-FEMA440, ACSM) and dynamic analysis methods.

5. NUMERICAL STUDY RESULTS

5.1. Preliminary Optimization

A comparison between the extended N2 method, proposed by Fajfar (Fajfar et al. 2005) to overcome the specificities of the plan-irregular buildings, and its former version was made in terms of storey drifts, normalized top displacements, lateral displacements pattern and chord rotations. The same comparison was made between the CSM with the features proposed in the ATC40 and in FEMA440.

The preliminary comparison between the N2 and the Extended N2 methods showed that for this building the Extended N2 procedure lead to better results than its original version. In the other hand, the CSM-FEMA440 proved to be a much improved version with respect to its CSM-ATC40 predecessor.

The Extended N2 method and the CSM-FEMA440 were chosen to be used in the subsequent plots.

5.2. Comparison between NSPs

Herein are presented some of the results obtained from the comparison of the different NSPs under study.

5.2.1. Top Displacements

A good manner in which to get a quick overview of how the different NSPs perform is to compute ratios of the values obtained with the latter for different response parameters and the corresponding median estimates coming from the dynamic analysis (Eqn. 5.1); clearly, ideally one would hope such ratios to tend to unity.

$$Top\ Displacement\ ratio = \frac{NSP's\ top\ displacement}{Time\ history\ median\ top\ displacement} \qquad (5.1)$$

Similar ratios were computed for other response quantities, such as interstorey drift, base shears, all in both X and Y directions, leading to similar observations and conclusions.

From Fig. 5.1 one can see that all the NSPs lead to conservative results of top displacements in the X direction for all the intensity levels studied. The CSM FEMA440 and the ACSM are the procedures that better estimate the top displacements.

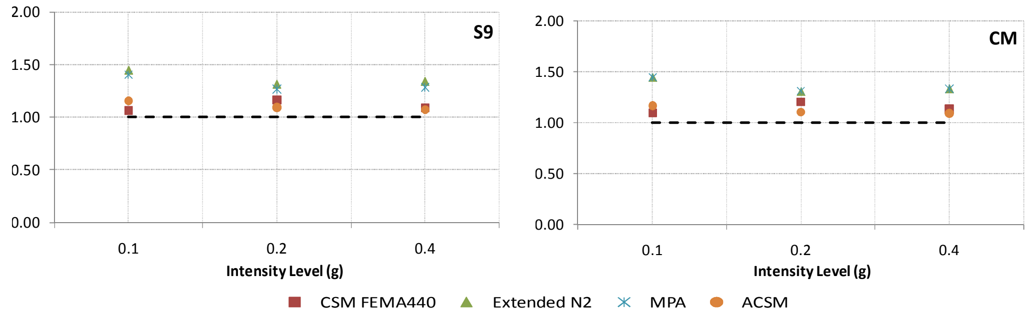
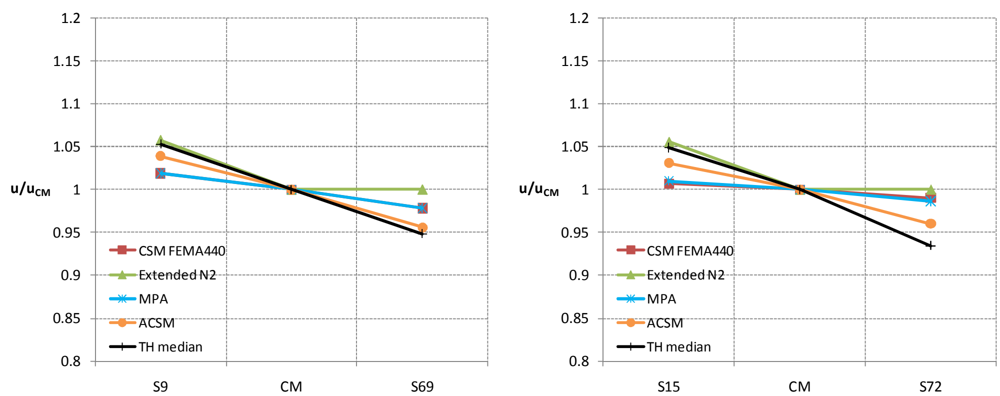


Figure 5.1. Top Displacements, X direction

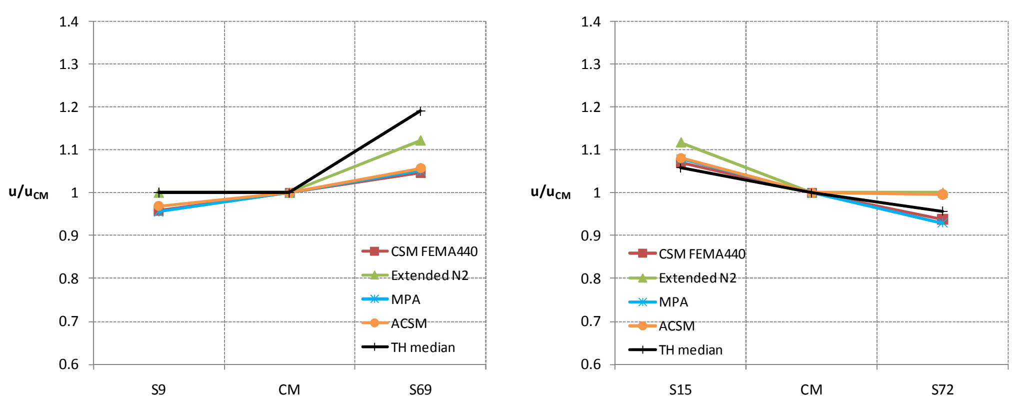
5.2.2. Torsional Rotation

In order to appreciate how well a given method is reproducing the torsional response of the building, it is customary to normalise the edge displacement values (u) with respect to those of the centre of mass (u_{CM}), Fig 5.2 and Fig 5.3.



(a) (b)

Figure 5.2. Normalized displacements at the top of the building, (a) X direction 0.2g, (b) X direction 0.4g.



(a) (b)

Figure 5.3. Normalized displacements at the top of the building, (a) Y direction 0.2g, (b) Y direction 0.4g.

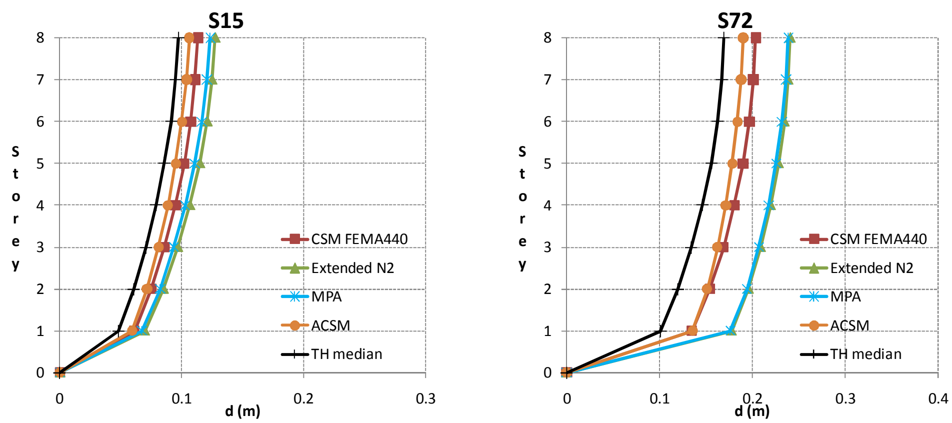
From Fig 5.2 a) it is clear that for 0.2g in the X direction the ACSM is the method that better estimates the torsional response of the columns S69 and the other NSPs lead to conservative results. The response of the column S9 is perfectly reproduced by the Extended N2 method, but all the other NSPs results lead to under conservative estimations. For this column the ACSM gets really close of the nonlinear dynamic results, although still under conservative.

For 0.4g (Fig 5.2 b) the Extended N2 method reproduces very well the response of the column S15. The other methods under predict the results of this column, although the ACSM gets really close to the nonlinear dynamic results. For column S72 the ACSM is the method that better predict the torsional motion in this side of the building. The other NSPs lead to conservative results.

From Fig. 5.3 a) one can observe that in the Y direction for 0.2g the Extended N2 method is the one that better estimates the torsional response in both S9 and S69 columns (although it is under conservative in column S69). The other NSPs lead to under conservative results for both columns.
For 0.4g in the Y direction, Fig. 5.3 b), all the NSPs lead to very good and conservative results in column S15. In column S72 only the ACSM and the Extended N2 method lead to conservative results.

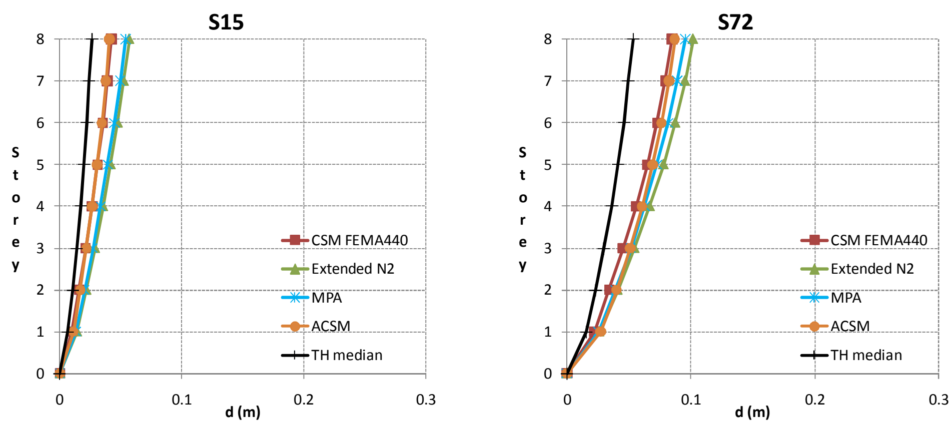
5.2.3. Displacement Pattern

The lateral displacement patterns were computed for different controlled nodes in both X and Y directions and for the different seismic intensity levels considered. Some of the plots are presented in Figs. 5.4 and 5.5.



(a) (b)

Figure 5.4. Lateral displacement patterns, (a) X direction, 0.2g, column S15; (b) X direction, 0.4g, column S72



(a) (b)

Figure 5.5. Lateral displacement patterns, (a) Y direction, 0.2g, column S15; (b) Y direction, 0.4g, column S72

From Figs. 5.4 and 5.5 one can observe that the building collapses due to a soft storey mechanism along the X direction. In fact, the first storey height is 5m while the rest of the floors have 2.7m height. This large difference between the height of the first floor and the second floor justifies the appearance of a soft storey mechanism at this level. This mechanism is developed along the X direction because the structure is less resistant and stiff in this direction. This fact can be explained because all the columns are elongated and have the higher dimension along the Y direction. In fact, for the same seismic intensity, the building presents bigger displacements in the X direction than in the Y direction.

Therefore, one can conclude that the building has an inadequate seismic design: a soft storey mechanism on the first floor; the stiffness not well distributed between the two, X and Y, directions. The Pushover analyses performed in this work can accurately capture both phenomena.
From Fig. 5.4 one can see in the X direction for 0.2g that all the NSPs can predict quite well the response of the building, including the soft storey mechanism in the first floor, giving all conservative results. In the X direction for 0.4g all the NSPs can reproduce the soft storey mechanism and all lead to conservative results. Although, the ACSM and the CSM FEMA440 are the ones that lead to closer results from the time history analyses.
From Fig. 5.5 it is observed that all the NSPs can reproduce the building's response in the Y direction, leading to conservative results.

5.2.4. Interstorey Drifts and Chord Rotations

In order to continue the study of the local response prediction by the different approaches, the storey drifts profiles given by the different NSPs are analysed and presented in Fig. 5.6.

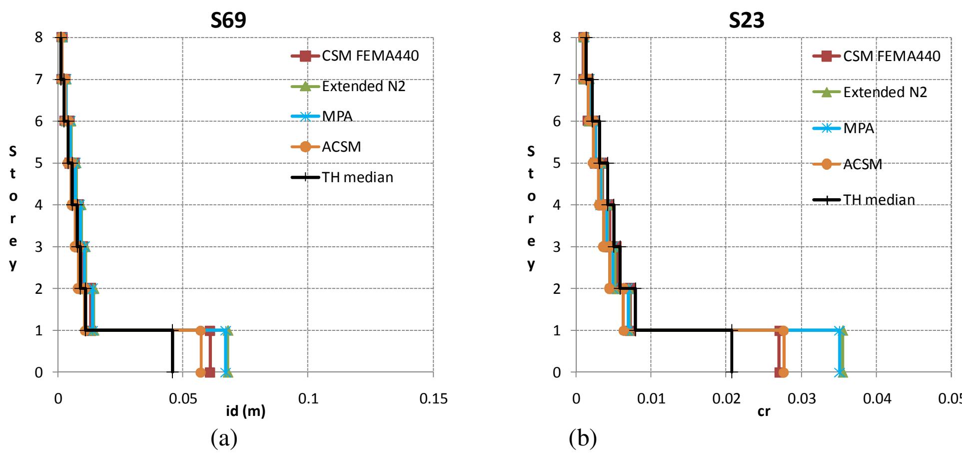


Figure 5.6. (a) Interstorey drifts, (a) X direction, 0.2g, column S69; (b) Chord rotations X direction, 0.4g, column S23

From Fig. 5.6 a) one can confirm that the building collapse is due to a soft storey mechanism in the first floor along the X direction, as explained in 5.2.3. Once again, all the NSPs can capture quite well this soft storey mechanism in the X direction in terms of interstorey drifts, being the ACSM the method that gets closer of the time history results. All the methods can reproduce the building's interstorey drifts in both directions leading to conservative results mostly in the Y direction. The same conclusions can be drawn for the chord rotations, Fig. 5.6 b).

6. CONCLUSIONS

In this paper, the effectiveness with which four commonly employed Nonlinear Static Procedures (CSM, N2, MPA, and ACSM) are able to reproduce the actual dynamic response of a real Turkish RC 8 storey building was assessed. The comparisons with the results obtained with nonlinear dynamic analysis seemed to show that, overall, all NSPs tend to lead to reasonably satisfactory and conservative results. From this study one could conclude that the building under analysis has an inadequate seismic design: soft storey mechanism (on the first floor) and incorrect stiffness distribution between the two directions (the Y direction is much more stiff than the X direction) – the building collapsed due to a soft storey mechanism on the first floor along the X direction. The Pushover analyses were able to reproduce these phenomena in a very accurate way. Particularly one can say that the ACSM and the CSM-FEMA440 are the methods that better matched the time history analyses. The good performance of the Adaptive Capacity Spectrum Method (ACSM) can be explained because such method uses: an adaptive displacement pushover (DAP) that takes into account the stiffness degradation and the period elongation by incrementally updating the applied lateral displacement pattern, and by considering the influence of higher modes; an equivalent SDOF structural displacement built on the current deformed pattern, avoiding any reference to a specific structural node. This means that each location contributes to the equivalent system displacement at that particular step, without reflecting any given (elastic or inelastic) invariant pattern. The results herein obtained with the ACSM seem to grant some validity in employing pushover analysis in the context of performance-based seismic assessment of 3D buildings.

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References

Antoniou S., Pinho R., 2004. Development and verification of a displacement-based adaptive pushover procedure. *Journal of Earthquake Engineering* **8 (5)**, 643-661.

Applied Technology Council (ATC), 2005. Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA 440 Report, Redwood City, CA.

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

Casarotti C., Pinho R., 2007. An Adaptive Capacity Spectrum Method for assessment of bridges subjected to earthquake action. *Bulletin of Earthquake Engineering* **5 (3)**, 377-390.

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

Chopra A.K., Goel R.K., 2002. A modal pushover analysis procedure for estimating seismic demands for buildings. *Earthquake Engineering and Structural Dynamics* **31**, 561-582.

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

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*, Tokyo-Kyoto, Japan, **Vol. 5**, 111-116.

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

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

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*, Berkley, USA., pp. 113-122.

Hancock J, Watson-Lamprey J, Abrahamson NA, Bommer JJ, 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., 1998. 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 Bridge and Structural Engineering*, Zurich, Switzerland; 15-22.

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

Bento R., Bhatt C., Pinho R., 2010. Using Nonlinear Static Procedures for Seismic Assessment of the 3D Irregular SPEAR Building. *Earthquakes and Structures – An Interantional Journal of Earthquake Engineering & Earthquake Effects on Structures*, in press.

SeismoSoft, 2006. SeismoStruct - A computer program for static and dynamic nonlinear analysis of framed structures, available online from http://www.seismosoft.com.