ASSESSING A REAL 3D TURKISH RC BUILDING USING NONLINEAR STATIC PROCEDURES

Bhatt C.[1], Bento R.[2] and Pinho R.[3]

ABSTRACT

The use of the NSP for plan-irregular 3D buildings has so far been the object of only restricted scrutiny. This limitation leads to a minor use of these methods to assess actual existing structures, the majority of which do tend to be irregular in plan. In this endeavour four commonly employed nonlinear static procedures (CSM, N2, MPA, ACSM) are applied in the assessment of a real Turkish RC 5 storey building. The building was modeled, using a nonlinear fibre-based structural analysis program, and subjected to a set of semi-artificial ground motions. The NSP's performance is tested in a wide range of intensities by comparing its results with incremental nonlinear dynamic analyses. Their accuracy is evaluated in terms of top displacement ratios, torsional rotation, lateral displacement patterns, interstorey drifts and chord rotations. A special attention will be given to the ACSM (Adaptive Capacity Spectrum Method) which performance in 3D plan-irregular buildings is recently being tested.

Introduction

The extension of the use of Nonlinear Static Procedures (NSP) to the case of plan-irregular structures has so far been the object of only restricted scrutiny (Chopra and Goel 2004; Fajfar, Marusic and Perus 2005; Pinho, Bento and Bhatt 2008), which effectively ends up by limiting significantly the employment of NSPs to assess actual existing structures, the majority of which tend to be irregular in plan. In addition, such few studies have typically concentrated on the application and verification of a single NSP approach, thus not providing useful elements of comparison between the different methodologies available.

In this work, therefore, four commonly employed nonlinear static procedures (CSM, N2, MPA, ACSM) are applied in the assessment of a real Turkish RC 5 storey building. Comparison with the results obtained with nonlinear dynamic analysis enables the evaluation of the accuracy of the different NSPs.

Case Study

The building selected for this work is a real Turkish reinforced concrete 5 storey building. It experienced the 1999 Golcuk earthquake without any damage.

[1]PhD Student, Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, Technical University of Lisbon, Portugal, cbhatt@civil.ist.utl.pt
[2]Associate Professor, Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, Technical University of Lisbon, Portugal, rbento@civil.ist.utl.pt
[3]Assistant Professor, Dept. of Structural Mechanics, University of Pavia, Italy, rui.pinho@unipv.it

The building is symmetric along the Y axis, Fig. 1a), and all the floors have the same height, Fig. 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).

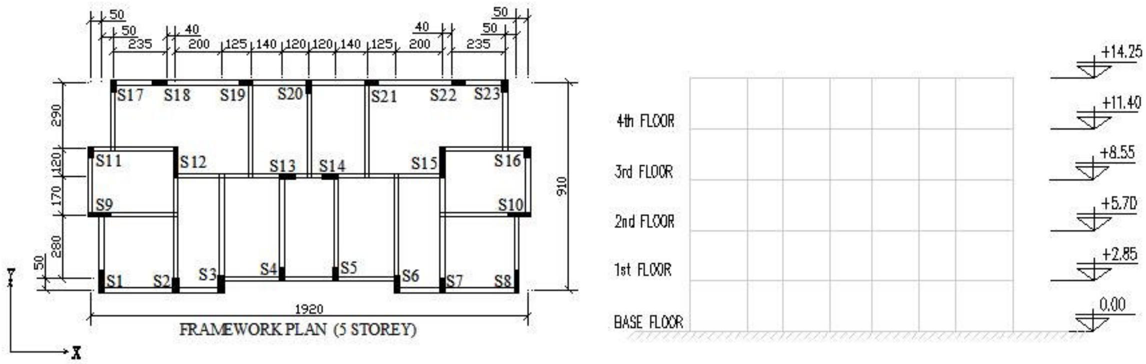


Figure 1. (a) Plan View (cm), (b) Lateral View (m).

The columns sections keep the same geometrical and reinforcement features along the height of the building. The beam sections are mainly 0.20x0.50m^2 except the two located in 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. For more details on the building's characteristics see (Vuran, Bal, Crowley and Pinho 2008).

Modelling Issues

The structural analysis software used in this study was SeismoStruct (SeismoSoft 2006), a freely downloadable fibre-based structural analysis program able to run eigenvalue analysis, nonlinear static (conventional and adaptive) analysis and nonlinear dynamic analysis. 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. To model the inelastic behaviour of the structural elements, a fibre element model is adopted, 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. To take into account for possible non-hysteretic sources of damping it was used a 5% tangent stiffness-proportional damping.

Materials

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) was adopted for the concrete. 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 that proposed by Menegotto and Pinto (1973) coupled with the isotropic hardening rules proposed by Filippou et al. (1983). An average yield strength of 371 MPa was assumed.

Diaphragm Modeling

The rigid diaphragm effect was modelled using the Nodal Constraints Rigid Diaphragm with Penalty Functions option. The penalty function exponent used was 10^7.

Controlled Nodes

In this work, 5 controlled nodes were chosen to evaluate the NSPs' performance: the stiff edge (SE), that corresponds to the column S1; the flexible edge (FE), the column S23; the centre of mass (CM), the central column S13 (CCl); and the central column S14 (CCR), see Fig. 1a).

Seismic Assessment – Numerical Study Description

Seismic Action

In this study, three bi-directional semi-artificial ground motion records were considered. These three are real records (Table 1) taken from the PEER's database website (PEER 2009).

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

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, 0.4, 0.6 and 0.8g.

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

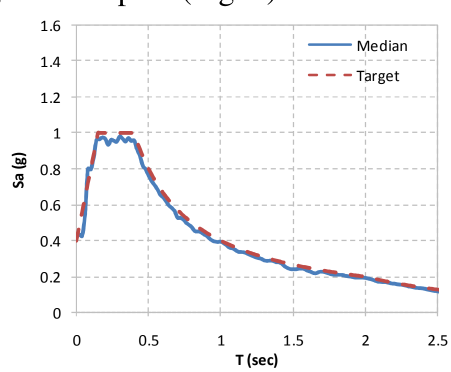


Figure 2. Response Spectrum, 0.4g.

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, Nicoletti, Tyrell 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, Marusic, Perus 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) introducing the 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.

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, lateral forces were applied to the structure in the form of two load patterns, mass-proportional and modal. 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.

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.

Numerical Study Results

Preliminary Optimization

A comparison between the extended N2 method, proposed by Fajfar (Fajfar, Marusic, Perus 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 showed that for this building both methods lead to close response predictions. 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.

Comparison between NSPs

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

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 (Eq. 1); clearly, ideally one would hope such ratios to tend to unity.

$$Top\ Displacement\ ratio = \frac{NSP's\ top\ displacement}{Time\ history\ median\ top\ displacement} \qquad (1)$$

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.

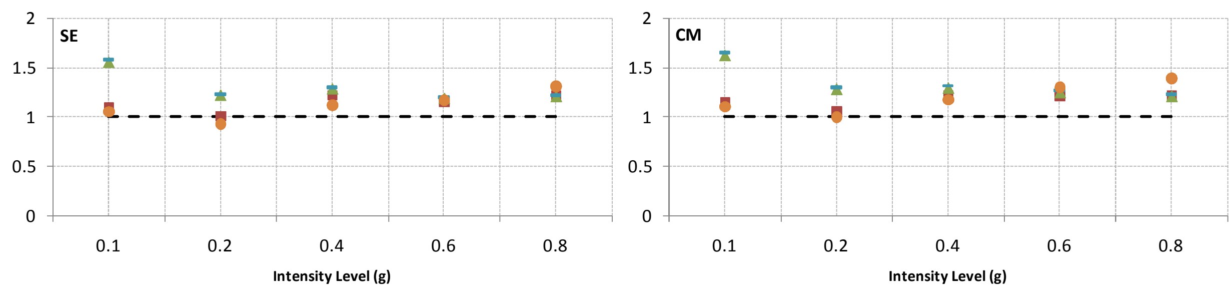


Figure 3. Top displacements, X direction.

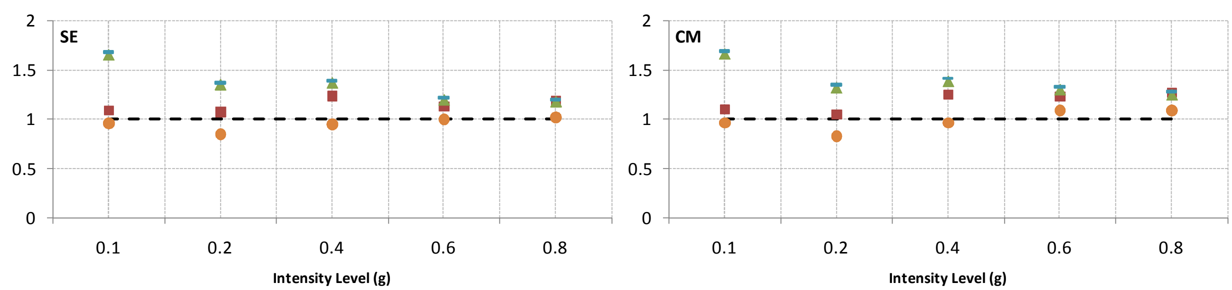


Figure 4. Top displacements, Y direction.

In Fig. 3 one can see that for 0.1g and 0.2g, the top displacements in the X direction, for all the controlled nodes, practically match the time history results for the CSM-FEMA440 and for the ACSM. For the other intensity levels all the NSPs lead to conservative results.

In the Y direction, Fig. 4, it is possible to see that the ACSM lead to results very close to the time history, except for 0.2g where it slightly underestimates the response. For 0.1g and 0.2g the CSM-FEMA440 presents very good results, and slightly overestimates the response for the other levels of intensity. The extended N2 method and the MPA tend to overestimate the response for all the intensity levels studied.

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 with respect to those of the centre of mass.

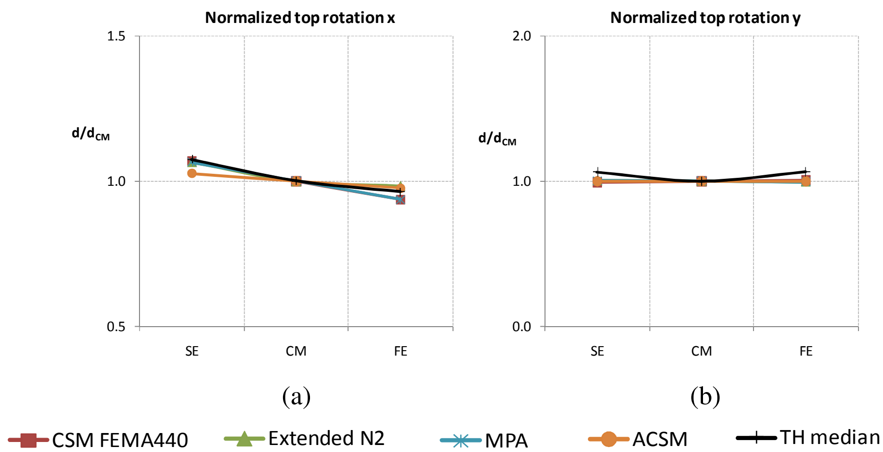


Figure 5. Normalized displacements at the top of the building, (a) X direction 0.4g, (b) Y direction 0.8g.

In the X direction, Fig. 5a), the NSPs can capture the behaviour of the stiff edge except the ACSM that slightly underestimates this response. In the flexible side of the building the ACSM and the Extended N2 are the methods that better estimate the response.

In the Y direction, Fig. 5b), all the NSPs gave generally the same results. They slightly underestimate the response in both sides of the building.

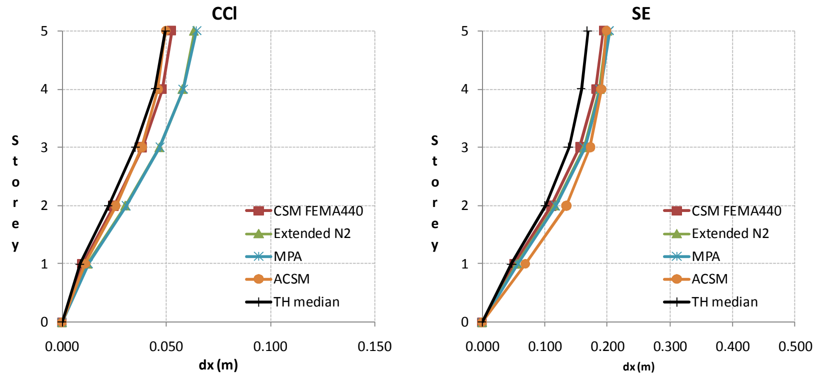
Lateral Displacement Pattern

The lateral displacements 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. 6 and 7.

In the X direction, for 0.2g, Fig. 6a) the CSM-FEMA440 and the ACSM lead to results very close to the time history. The other methods lead to conservative results.

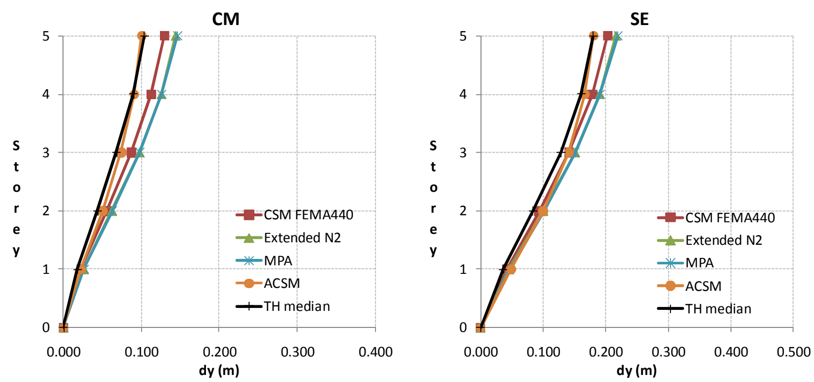
In the X direction, for 0.6g, Fig. 6b) all the methods present similar results. They are all conservative in respect to the time history.

In the Y direction, Fig. 7, all the NSPs lead to conservative results. The ACSM seems to be the one that better estimates the building's response in this direction.



(a) (b)

Figure 6. Lateral displacement pattern, X direction, (a) 0.2g, (b) 0.6g.

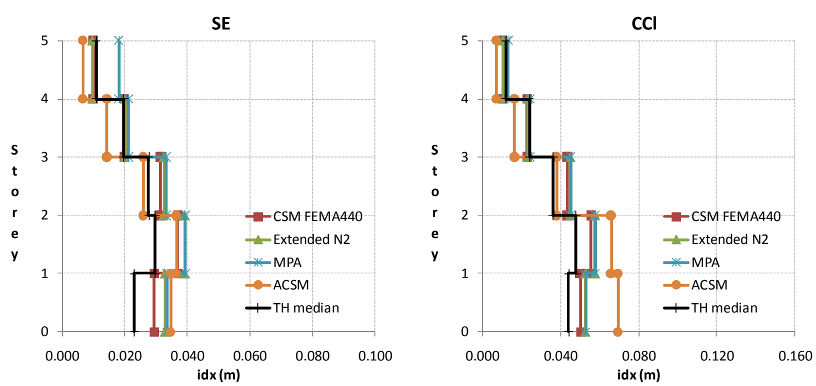


(a) (b)

Figure 7. Lateral displacement pattern, Y direction, (a) 0.4g, (b) 0.6g.

Interstorey drifts

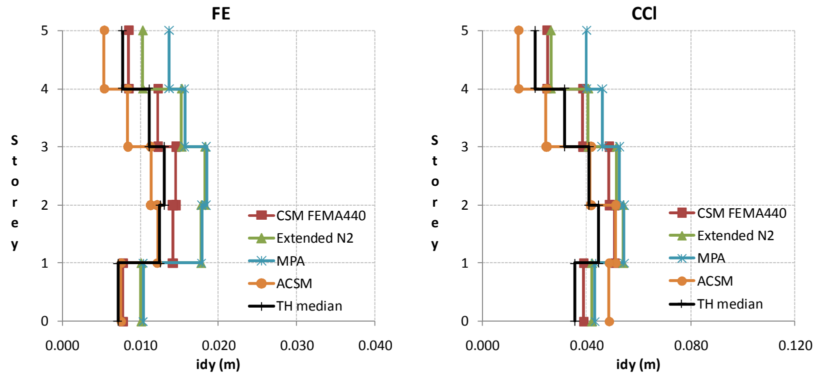
In order to continue the study of the local response prediction by the different approaches, the storey drifts profiles given by the different NSPs are analysed and presented in Figs. 8 and 9.



(a) (b)

Figure 8. Interstorey drifts, X direction, (a) 0.4g, (b) 0.6g.

In the X and Y direction, Figs. 8 and 9 respectively, the NSPs can capture the behaviour of the structure in terms of interstorey drifts. They general lead to conservative results.



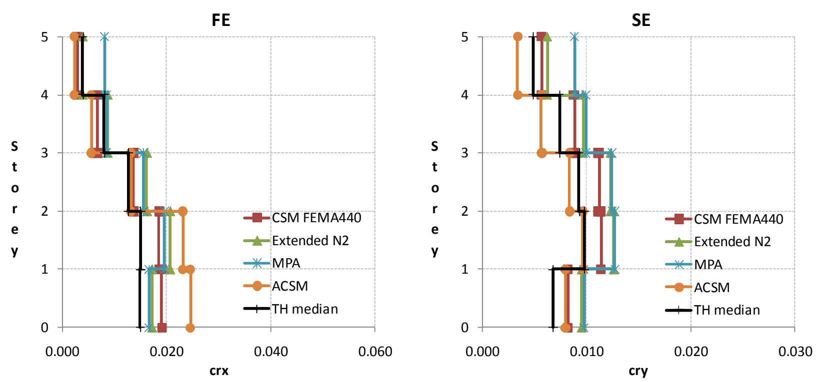
(a) (b)

Figure 9. Interstorey drifts, Y direction, (a) 0.2g, (b) 0.6g.

The ACSM presents some slightly non conservative values for the 3 upper storeys except for 0.6g where it underestimates the storey drifts only in the 2 upper storeys in both directions.

Chord Rotations

The same conclusions taken for the interstorey drifts can be drawn for the chord rotations, Fig. 10.



(a) (b)

Figure 10. Chord rotations, (a) X direction 0.6g, b) Y direction 0.4g.

Conclusions

In the current endeavour, the effectiveness with which four commonly employed Nonlinear Static Procedures (CSM, N2, MPA, ACSM) are able to reproduce the actual dynamic response of a real Turkish RC 5 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.
Particularly one can say that: the CSM-FEMA440 lead to better results than the CSM-ATC40; 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.
Additional work considering other real buildings must be carried out before any definitive conclusions and recommendation might be made.

Acknowledgments

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