ASSESSING THE 3D IRREGULAR SPEAR BUILDING WITH NONLINEAR STATIC PROCEDURES

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ABSTRACT

The employment of Nonlinear Static Procedures (NSP) in the seismic assessment of existing structures (or design verification of new ones) has gained considerable popularity in the recent years, backed by a large number of extensive verification studies that have demonstrated its relatively good accuracy in estimating the seismic response of buildings that are regular in plan (and hence can be analysed by means of planar 2D frame models). The extension of such use to the case of plan-irregular structures, however, has so far been the object of only restricted scrutiny, which effectively ends up by limiting significantly the employment of NSPs to assess actual existing structures, the majority of which do tend to be irregular in plan. In this work, therefore, four commonly employed nonlinear static procedures (CSM, N2, MPA, ACSM) are applied in the assessment of the well-known SPEAR building, an irregular 3D structure tested in full-scale under pseudo-dynamic conditions, and subjected to bi-direction seismic loading. Comparison with the results obtained with nonlinear dynamic analysis of a verified model of the structure then enables the evaluation of the accuracy of the different NSPs.

KEYWORDS: Seismic assessment, 3D irregular SPEAR building, Nonlinear Static Procedures

1. 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 et al., 2005; Moghadam and Tso, 2000; Penelis and Kappos, 2002), which effectively ends up by limiting significantly the employment of NSPs to assess actual existing structures, the majority of which do 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 the well-known SPEAR building, an irregular 3D structure tested in full-scale under pseudo-dynamic conditions, and subjected to bi-direction seismic loading. Comparison with the results obtained with nonlinear dynamic analysis of a verified model of the structure then enables the evaluation of the accuracy of the different NSPs.

2. CASE STUDY –THE SPEAR BUILDING

The building selected for the current work is the so-called “SPEAR building” built to full-scale and then tested within the European research project SPEAR (Fardis and Negro, 2006), so as to represent typical old constructions in Southern Europe without specific provisions for earthquake resistance. Its geometry and all the issues concerned with modelling and modelling validation are described in a poster presentation entitled "Modelling of the horizontal slab of a 3D irregular building for nonlinear static assessment" (Bhatt et al., 2008), also presented in this conference.

2.1. Dynamic Properties

The modal properties, in terms of periods and effective modal mass percentages, of the SPEAR building are reported in Table 2.1, attesting the torsion-dominated characteristics of this structure; no pure translational modes are present, the response of the building cannot be reasonably evaluated using separate 2D models for each orthogonal direction.

Table 2.1 Periods and effective modal mass percentages

	Translation mode along X			Translation mode along Y			Torsional mode		
	T [sec]	UX (%)	UY (%)	T [sec]	UX (%)	UY (%)	T [sec]	UX (%)	UY (%)
1st modes	0.62	60.47	7.82	0.44	3.14	31.60	0.53	23.48	42.98
2nd modes	0.22	7.41	0.77	0.14	0.35	7.86	0.18	2.82	3.91

3. NUMERICAL STUDY - DESCRIPTION

3.1. Seismic Action

In this study, seven bi-directional semi-artificial ground motion records from the SPEAR project were considered (Table 3.1); these had been fitted to the EC8 elastic design spectrum (Type 1 soil C). The ground motions were scaled for intensity levels of peak ground accelerations of 0.05, 0.1, 0.2 and 0.3g. For the NSPs the response spectra used are the median of the response spectra defined, compatible with the accelerograms adopted (Figure 1).

Table 3.1 Ground motion records considered (Fardis and Negro, 2006).

Earthquake Name	Station Name
Imperial Valley 1979	Bonds Corner
Loma Prieta 1989	Capitola
Kalamata 1986	Kalamata – Prefecture
Montenegro 1979	Herceg Novi
Friuli 1976	Tolmezzo
Montenegro 1979	Ulcinj2
Imperial Valley 1940	El Centro Array #9

3.2. Considered Nonlinear Static Procedures (NSPs)

As mentioned above, the accuracy of existing NSPs in assessing the seismic response of the irregular SPEAR building is herein scrutinised through a comparison with the results of incremental nonlinear dynamic analysis. The NSPs may be split into two main groups.

The first set of NSPs comprises the pioneering Capacity Spectrum Method (CSM), introduced by Freeman and collaborators (1975 and 1998) and implemented in ATC-40 guidelines (1996), and the equally innovative N2 method suggested by Fajfar and co-workers (1988 and 2000) and later included in Eurocode 8 (CEN, 2005). These first proposals are characterised by their simplicity and usually consider a first mode and/or uniform load

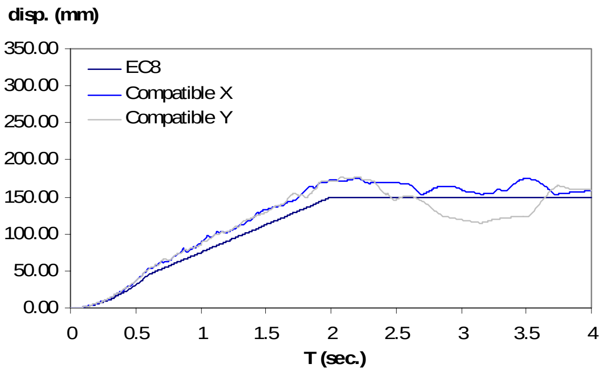


Figure 1 Median displacement spectra compatible with the accelerograms used for 0.2g

distributions in 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 (2002 and 2004) on a Modal Pushover Analysis (MPA), of Kalkan and Kunnath (2006) who propose an Adaptive Modal Combination Procedure (AMCP) and of Casarotti et al. (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. Unfortunately, however, time constraints did not allow the authors to develop an adaptive pushover algorithm that would consider each single higher mode in independent fashion, for which reason no results for the AMCP method will be given in the subsequent sections, most regrettably.

3.3. 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, lateral forces were applied to the structure in the form of two load patterns, uniform and modal. In the latter case, the displacements were applied on all mass nodes of the structure and spectral scaling was considered. 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 seven bidirectional semi-artificial ground motion records were employed in 4 different configurations: X+Y+, X+Y-, X-Y-, X-Y+. The results in terms of top displacements, interstorey drifts and top rotation 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.

4. NUMERICAL STUDY - RESULTS

The results obtained in the performed analyses are presented in this section. The monitored nodes are schematically represented in Figure 2, where SE represents the stiff edge, FE the flexible edge and CM the centre of mass. A central node corresponding to the central column, was named as node C.

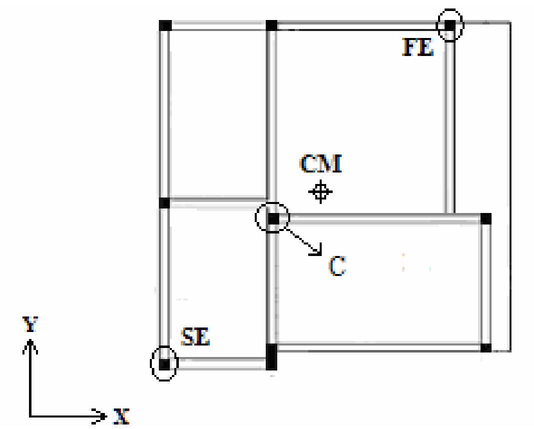


Figure 2 Monitored nodes

The preliminary comparison between the N2 and the Extended N2 methods showed clearly that the latter leads to better response predictions, hence all subsequent N2 results will refer to this approach (termed also as "N2 torsion"). Similarly, the CSM-FEMA440 proved also to be a much improved version with respect to its CSM-ATC40 predecessor, and was thus adopted on all subsequent stages of the work.

4.1. Pushover curves

Exemplificatively, some of the obtained pushover curves are plotted in Figure 3 against the median dynamic analysis results; (i) maximum top floor displacement against maximum base shear (max Displ vs. max BS) in a given direction independent of time at which they occur, (ii) maximum base shear against the corresponding, in time, displacement value (Displ vs. max BS), (iii) maximum displacement against the corresponding base shear (max Displ vs. BS).

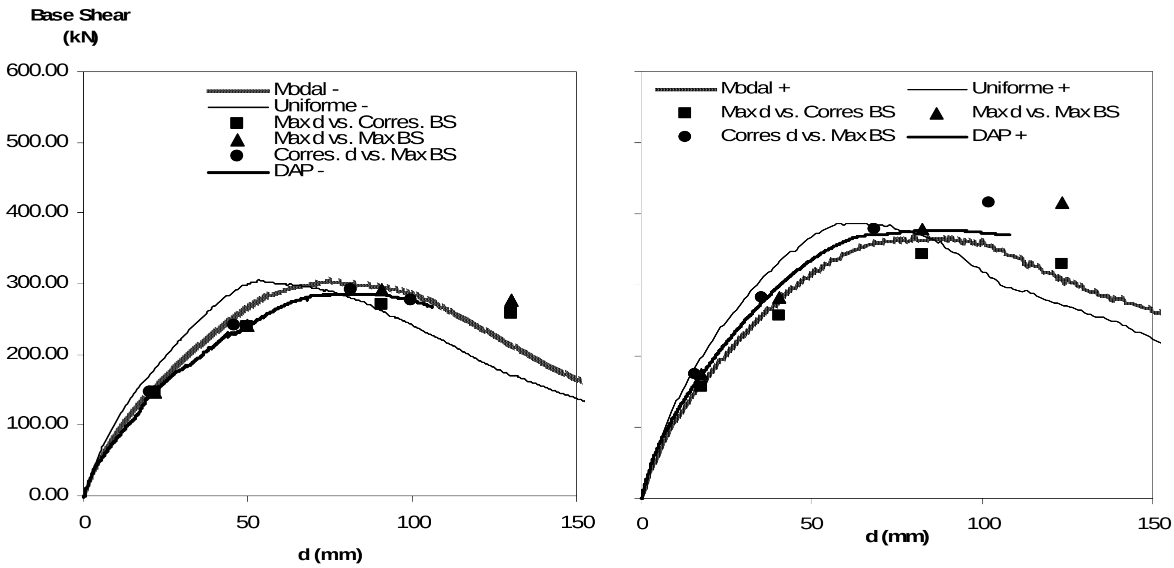


Figure 3 Pushover curves in X and Y direction

The pushover curves for the X direction are quite similar in the positive and negative direction. Some differences were on the other hand found in the Y direction, mainly due to the behaviour of column C6. From the results obtained it is also possible to notice that, in general the pushover curves fall close to the time-history points max Displ vs. max BS, Displ vs. max BS and max Displ vs. BS.

4.2. NSP/Dynamic analysis prediction ratios

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 (Casarotti et al., 2007); clearly, ideally one would hope such ratios to tend to unity.

In Figure 4, such ratios are given for the top displacements in the Y direction, at the FE, SE and CM locations, being readily observed that, in general, all NSPs lead to reasonably close predictions at the Centre of Mass. For the Flexible and Stiff Edges, on the other hand, the performance of the different methods is not consistent throughout the entire set of intensities, though perhaps one may identify the N2 and ACSM approaches as being those that lead to better response estimates. In general, all the NSPs lead to non-conservative values. The exception is the ACSM, for almost all the seismic intensity levels. 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.

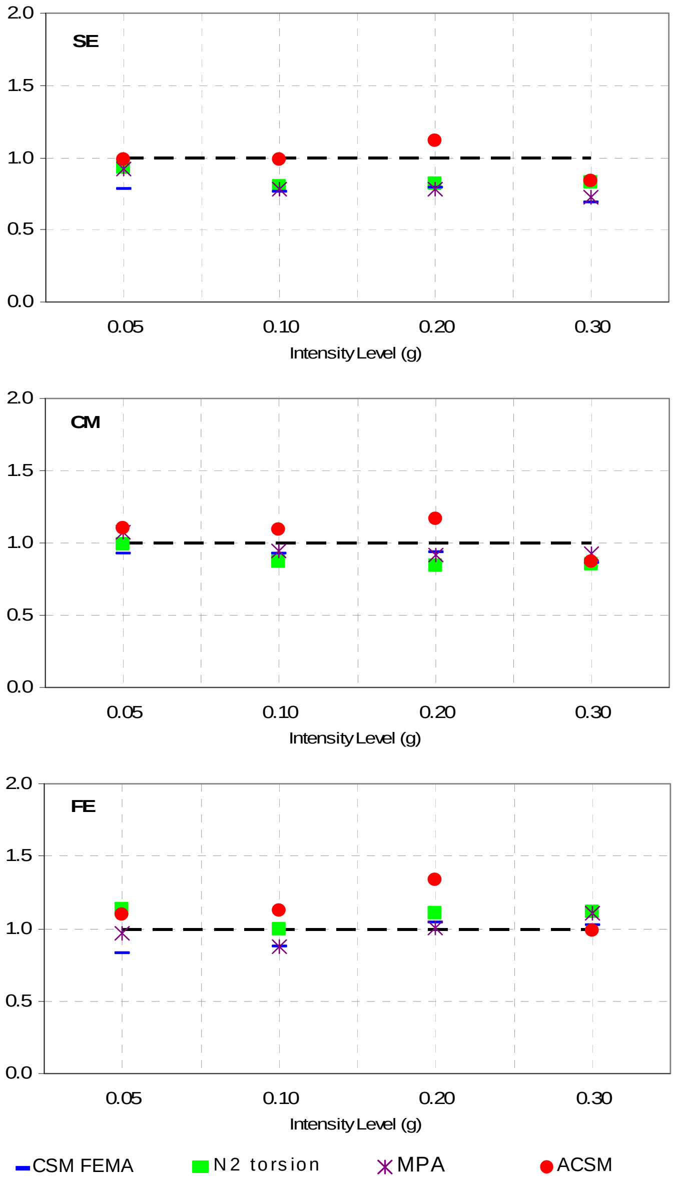
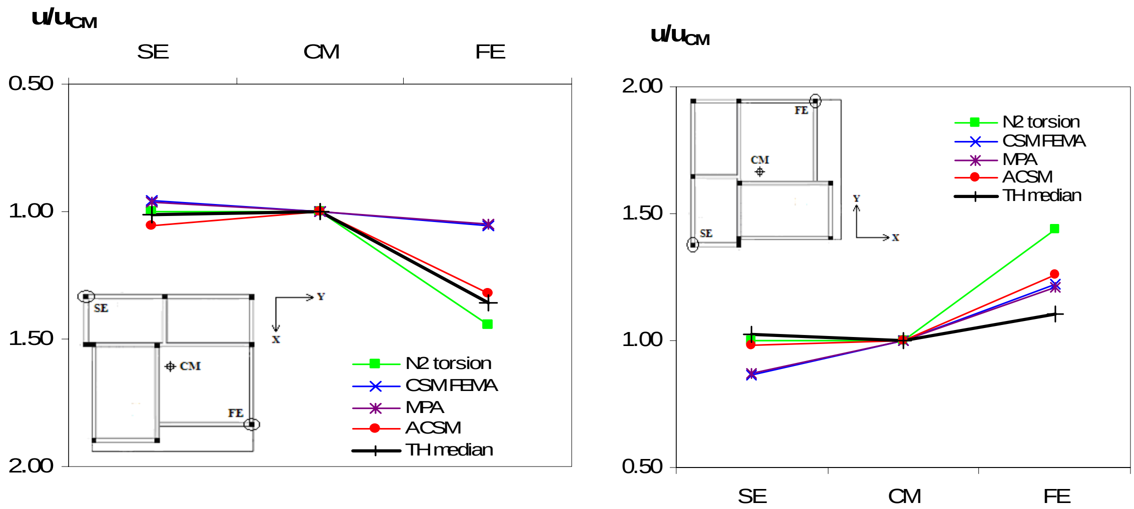


Figure 4 Top displacements in the Y direction

4.3. Torsional rotation

In order to appreciate how well a given method is reproducing the torsional response of the building structure, it is customary to normalise the edge displacement values with respect to those of the centre of mass. Exemplificatively, the X-direction torsional response for an intensity level of 0.1g and the Y-direction torsional response for an intensity level of 0.2 g are shown in Figure 5, where it is noticed that the N2 and ACSM approaches again seem to feature a slight advantage with respect to the other methods, even if then both over-estimate significantly the Flexible Edge response of Figure 5(b).



(a) X direction, intensity 0.1g (b) Y direction, intensity 0.2g

Figure 5 Normalized displacements at the top of the building

4.4. Storey drifts

A final insight into the prediction of the local response by the different approaches can be obtained through the inspection of the storey drifts profiles given by the different NSPs. In Figure 6, in the previous page, it is therefore observed that all methods manage to correctly reproduce the correct response mechanism for intensity levels of 0.05g, 0.10g and 0.20g. However, the ACSM is the only method able to lead to conservative results. This latter response parameter seems to confirm once again that from an overall viewpoint all Nonlinear Static Procedures tend to lead to similar results.

5. 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 the well-known SPEAR building was assessed. The comparisons with the results obtained with nonlinear dynamic analysis of a verified model of the structure seemed to show that, overall, all NSPs tend to lead to reasonably satisfactory results.

In addition, it was also observed that the Adaptive Capacity Spectrum Method (ACSM) apparently managed to follow slightly better the change of response characteristics with the increase of seismic intensity, most likely because of the fact that 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.

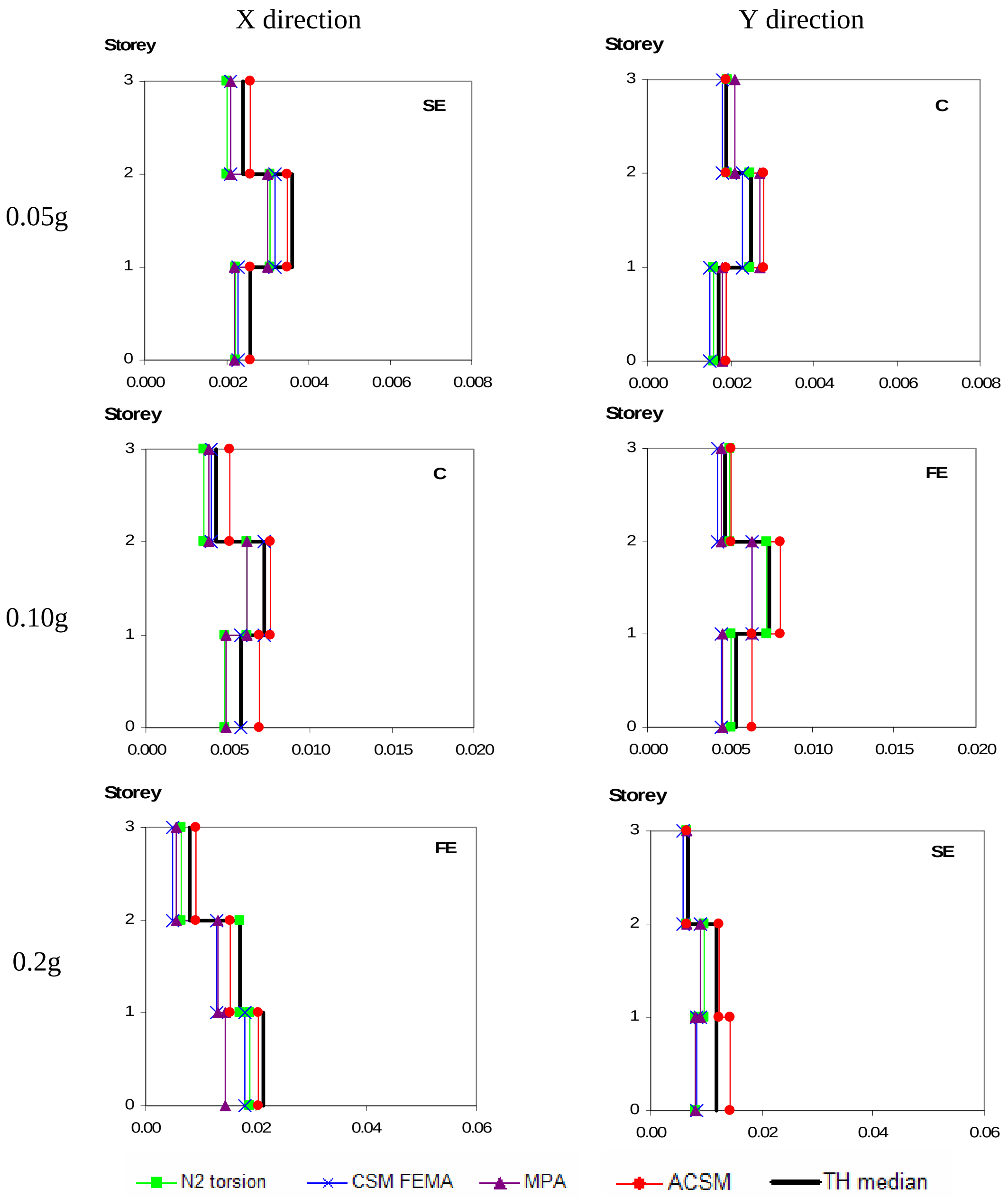


Figure 6 Storey drifts in nodes C, FE and SE for different intensity values

The results obtained in this study with the proposed static procedure seem to grant some validity in employing pushover analysis in the context of performance-based seismic assessment of 3D irregular buildings. They also seem to be in-line with similar studies carried out for plane frames (Pinho *et al.*, 2008a) and bridges (Pinho *et al.*, 2008b). Nonetheless, given the preliminary nature of this study, it is obviously advocated that additional work considering different 3D buildings must be carried out before any definitive conclusions and recommendations might be made.

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