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The Extended Adaptive Capacity Spectrum Method for the Seismic Assessment of Plan Asymmetric Buildings

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The use of nonlinear static procedures (NSPs) on the seismic assessment of real existing plan irregular structures has so far been studied by a limited number of authors. This fact limits the application of such methods to assess current existing structures, the majority of which are irregular in plan. An extended version of the Adaptive Capacity Spectrum Method (ACSM) for the seismic assessment of plan irregular buildings is presented in this paper. The novelty of this proposal is to comprise the most accurate features of commonly used NSPs in order to overcome the problems that subsist in three dimensional pushover analyses. The accuracy of the procedure is tested in three plan irregular real buildings. The results are compared with the Capacity Spectrum Method (CSM) with the features proposed in FEMA440, with the Extended N2 method for plan asymmetric structures, with the Adaptive Capacity Spectrum Method (ACSM) and with the most exact nonlinear dynamic analyses. Several seismic intensities are tested, in order to evaluate the performance of the procedure in different stages of structural inelasticity.

INTRODUCTION

The use of nonlinear static procedures on the seismic assessment of simple structures (planar frames and bridges) is backed by a large number of extensive verification studies that have demonstrated their relatively good accuracy. However, the extension of such use to the case of 3D irregular structures has been studied by a limited number of authors (Fajfar et al. 2005a) and b), Chopra and Goel 2004, D'Ambrisi et al. 2009, Erduran and Ryan 2011). This fact limits the application of such procedures to assess actual existing structures, the majority of which are non-regular in plan.

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The Adaptive Capacity Spectrum Method (ACSM) firstly proposed by Casarotti and Pinho (2007) for the seismic assessment of bridges, combines elements from the Displacement Based Design (Priestley et al. 2007) and the Capacity Spectrum Method (CSM) (Freeman 1998). The ACSM uses an adaptive displacement pushover (DAP) (Antoniou and Pinho 2004) and employs a MDOF to SDOF transformation based on the current deformed pattern of the structure. The target displacement is calculated using a reduced response spectrum. The method has been tested by several researchers on the seismic assessment of planar frame buildings (Pinho et al. 2008) and bridges (Casarotti and Pinho 2007, Pinho et al. 2009). The results obtained seem quite optimistic regarding the accuracy of this procedure on regular structures. However, the performance of the ACSM on plan asymmetric 3D buildings is far from being consensual. In fact, the method seems not to be able to reproduce in an accurate fashion the torsional motion of this type of structures.

In order to overcome this limitation, an extended version of the ACSM for plan irregular buildings is presented in this paper, in which the ACSM is complemented with the most accurate features of other commonly used nonlinear static methods. The novelty of this methodology is to comprise the most accurate features of the original ACSM, FEMA440 (ATC 2005) and Extended N2 method for plan asymmetric buildings (Fajfar et al. 2005a) and b)), in order to overcome the problems associated with three dimensional pushover analyses.

The adaptive displacement pushover and the MDOF to SDOF transformation are kept from the original ACSM. The computation of the target displacement is made using the algorithm proposed in FEMA440 for the calculation of the effective period, damping, reduction factor and the new Modified Acceleration Displacement Response Spectrum (MADRS). This algorithm was proven to be accurate in several studies, such as Bhatt and Bento (2011). The torsional effects are taken into account using the correction factors proposed by Fajfar and his team in the Extended N2 method for plan asymmetric buildings.

The performance of the Extended ACSM is herein tested and compared with the original methods in which it is based. The case studies used in this work are three real existing reinforced concrete (RC) buildings asymmetric in plan with three, five and eight storeys. Comparison of the results obtained with nonlinear dynamic analyses, through the use of semi-artificial ground motions, enables the evaluation of the accuracy of the proposed NSP. The large parametric studies were performed for several seismic intensities in order to evaluate the performance of the procedure when the building goes through different stages of structural inelasticity.

This work aims at contributing to the progress beyond current state of the art taking a further step on the three dimensional pushover problem in order to reach to more consolidated conclusions.

THE EXTENDED ACSM FOR PLAN ASYMMETRIC BUILDINGS

The first step of the procedure consists on the development of a 3D nonlinear model of the building, in which the nonlinear monotonic behavior of the materials is perfectly defined. For such, one can adopt a distributed plasticity strategy through the use of fibre elements, or a concentrated plasticity option through the definition of plastic hinges - in terms of Moment-Curvature section behavior and plastic hinge length. In this work a distributed plasticity strategy was adopted.

Displacement based adaptive pushover (DAP)

The capacity curves of the 3D building model are obtained through a displacement based adaptive pushover (DAP) introduced by Antoniou and Pinho (2004). The pushover is performed separately in each X and Y directions, with the + and – sense in each direction, resulting in four analyses per building. The DAP algorithm is available in several software packages, such as SeismoStruct (Seismosoft 2008) and OpenSees (Mckenna et al. 2009).

Characterization of the equivalent SDOF

The characterization of the adaptive capacity curve of the SDOF is computed step by step from the DAP analysis. This transformation was proposed by Casarotti and Pinho (2007), and it is based on the principle of Substitute Structure analogy which was also derived using the principle of the equal work developed. The equivalent SDOF adaptive capacity curve is defined step-by-step, based on the actual deformed shape at each analysis step.

Calculation of the target displacement

The target displacement of the equivalent SDOF is calculated by intersecting its adaptive capacity curve with the elastic response spectrum reduced (in the acceleration-displacement format) corresponding to the seismic action considered, Figure 1. The intersection point is called performance point, and corresponds to the inelastic acceleration and to the target displacement of the equivalent SDOF.

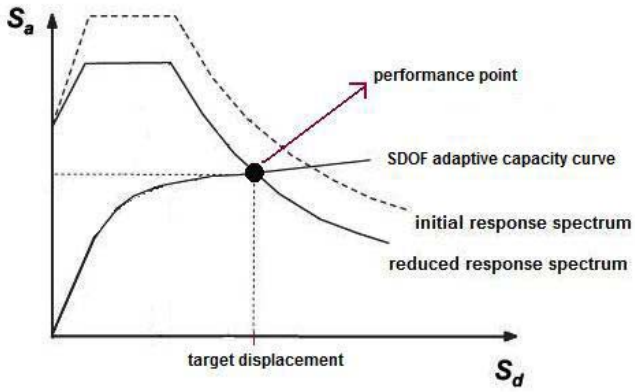


Figure 1. Calculation of the performance point and the target displacement of the equivalent SDOF.

In the present study, the demand was defined by real earthquake spectra rather than a smoothed design spectrum. In these cases, more than one intersection with the capacity curve can be found when using the Extended ACSM. It has been verified in (Casarotti and Pinho 2007) that often only one of those intersections leads to convergence with the damping value. Usually it is the one corresponding to the largest displacement value. When more than one intersection provides convergence with the damping, it was concluded that the one corresponding to the largest displacement leads to results closer to the nonlinear dynamic analyses. Choosing the largest deformation as the performance point is a conservative assumption, since the different intersections lead to approximate values of base shear (because they happen in the post-elastic range) but different displacement estimations.

As it was previously mentioned, the elastic response spectrum is reduced using factors dependents on the effective damping. The effective period, the effective damping, the spectral reduction factor for effective damping, the modified acceleration-displacement response spectrum (MADRS), are calculated based on the proposals recommended in FEMA440 report presented in 2005 (ATC).

Torsional correction factors

At this stage a linear response spectrum analysis of the 3D mathematical model is performed, applying the excitation in both directions and combine them using the SRSS rule. In this analysis, the materials that constitute the building have an elastic behavior, and the response spectrum used is the elastic one.

The torsional correction factors calculated herein are based on the proposal of Fajfar and his team (Fajfar et al. 2005a) and b)), to the extension of the N2 method for plan asymmetric buildings. The conclusions drawn by Fajfar and his team showed that in the majority of the buildings it is possible to calculate an upper bound of the torsional amplifications through a linear response spectrum analysis. The torsional correction factors are determined calculating the ratio between the normalized top displacements (in the last floor) obtained from the linear response spectrum analysis and from the pushover analysis. The normalized top displacements are obtained normalizing the displacement in a certain location of the roof in respect to those in the centre of mass of the roof. If the normalized top displacement obtained from the linear response spectrum analysis is smaller than 1.0, one should consider it 1.0 in order to avoid any de-amplification of displacements due to torsion given by this elastic analysis. Note that, each location has a torsional correction factor for the X direction and another one for the Y direction. The final structural response is obtained by multiplying the quantity under analysis in an element, in a certain location in plan, by the torsional correction factor calculated for that location.

Flowcharts describing the Extended ACSM for a plan irregular building are presented in Figures 2 and 3.

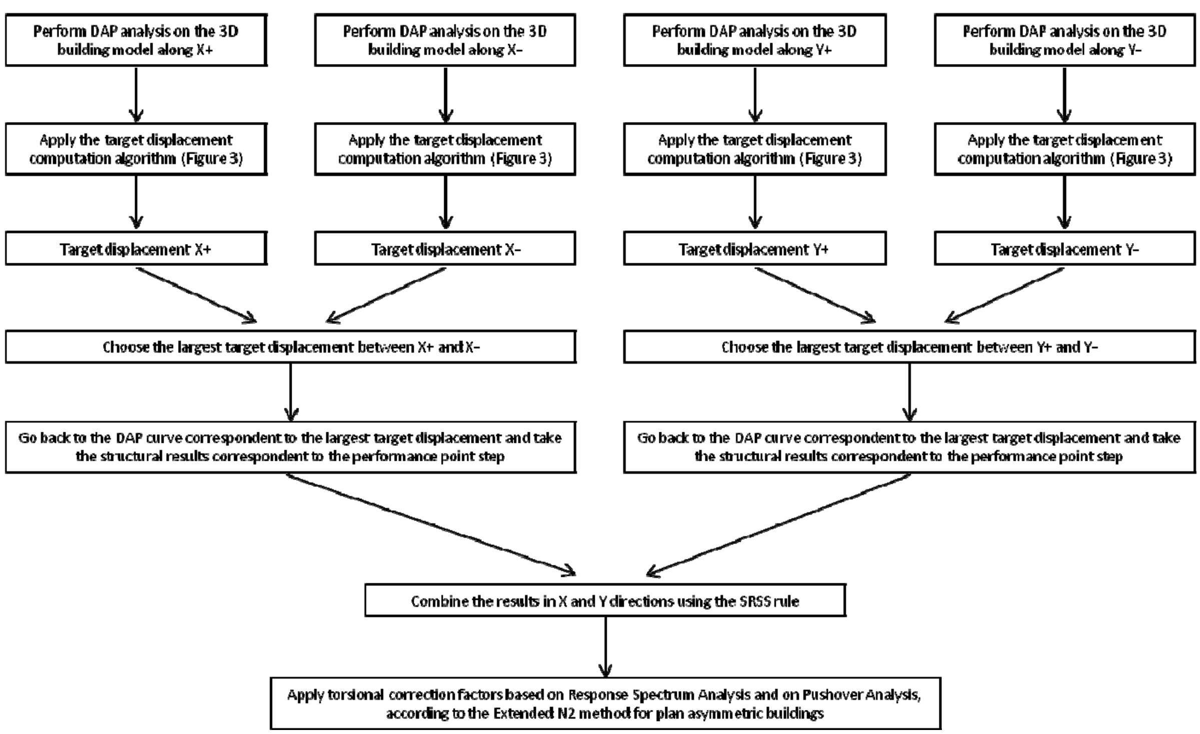


Figure 2. The Extended ACSM algorithm.

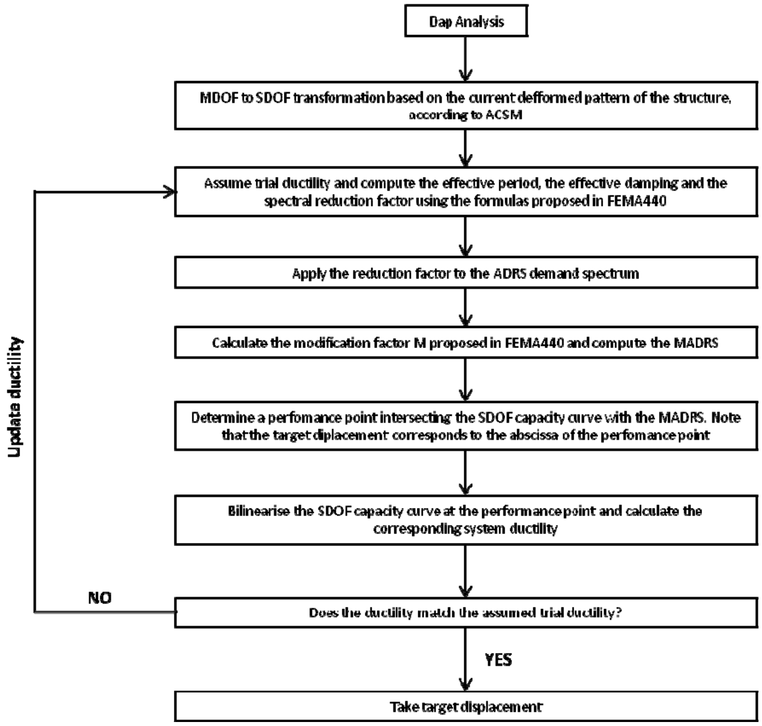


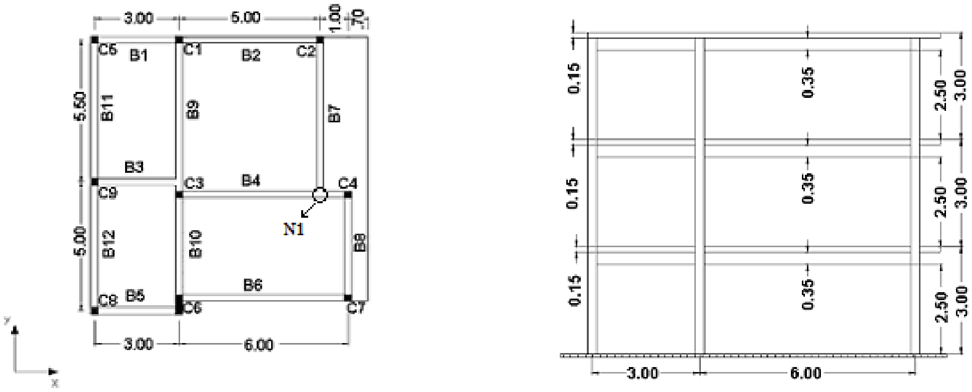
Figure 3. Target displacement computation algorithm of the Extended ACSM.

CASE STUDIES

The case studies analysed in this work are real existing buildings asymmetric in plan: a three storey building, representing typical old constructions in Greece and in the Mediterranean region; a five storey and an eight storey buildings located in Turkey.

The first case study to be analysed is the SPEAR building. It represents typical existing three-storey buildings in the Mediterranean region following Greece's concrete design code in force between 1954 and 1995. This structure was designed only for gravity loads based on the construction practice applied in the early 1970s that included the use of smooth rebars. It was tested in full-scale under pseudo-dynamic conditions, and subjected to bi-direction seismic loading, at JRC Ispra within the European SPEAR project framework. Plan and elevation views are shown in Figure 4, whilst further details on the structure and its pseudo-dynamic testing can be found in (Fardis 2002) and (Fardis and Negro 2006).

The building is plan-asymmetric in both X and Y directions but it is regular in elevation (Figure 4).

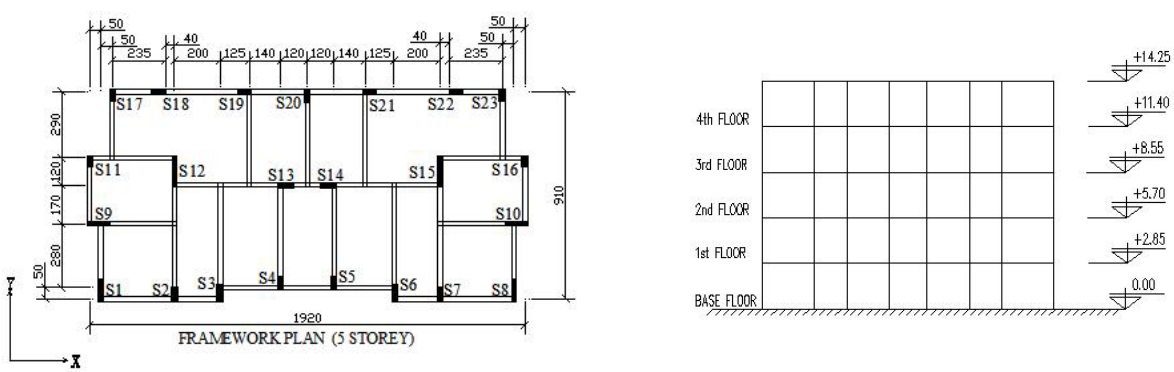


(a) (b)

Figure 4. Three storey building (a) Plan View (m), (b) Lateral View (m).

The second case study is a real 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.

The building is asymmetric in plan along the X axis, Figure 5a), and all the floors have the same height, Figure 5b). There are beams framing into beams leading to possible weak connections in the structure. There are also walls and elongated columns (wall-like column), as presented in Figure 5a).

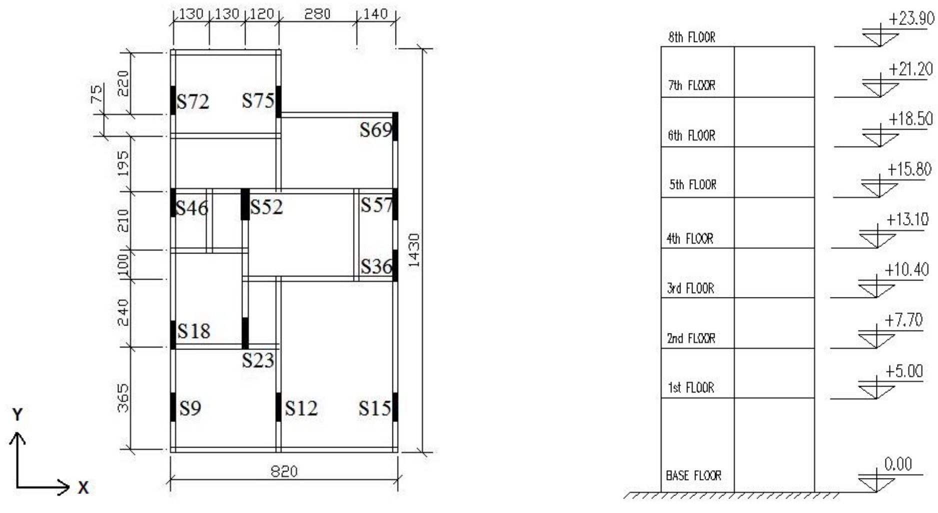


(a) (b)

Figure 5. Five storey building (a) Plan View (cm), (b) Lateral View (m).

The columns sections keep the same geometrical and reinforcement features along the height of the building. For more details on the building's characteristics see (Vuran et al. 2008).

The third case study selected for this work is also a real Turkish reinforced concrete 8 storey building. It is a plan-irregular structure since it is asymmetric along the X and Y axis, Figure 6a). The building was also designed according to the 1975 Seismic Code of Turkey.



(a) (b)

Figure 6. Eight storey building (a) Plan View (cm), (b) Lateral View (m).

The first storey height amounts to 5.00m and the other floors have the same 2.70m height, Figure 6b). There are beams framing into beams leading to possible weak connections in the structure. There are also walls and elongated columns (wall-like column), as presented in Figure 6a), with the higher dimension always along the Y direction. For this reason, the structure will be more stiff and resistant along the Y direction.

MODELING OPTIONS

The 3D nonlinear models of the buildings under analysis in this work were developed using SeismoStruct (Seismosoft 2008), a fibre element based finite element software. It was assumed a distributed plasticity on the nonlinear modeling of the members, being their inelasticity modeled through the use of fibre element models.

The buildings were simulated using 3D space frame models, considering geometric nonlinearity and distributed material inelasticity through the use of displacement based elements. Each element was discretized into four or five sub-elements with two integration Gauss points each. At this points, fibrerized cross-sections were defined assigning to each fibre an appropriate material constitutive relationship, as described below. The sectional responses were obtained by integrating the material responses across a section using mid-point rule. The element responses were determined using the Gauss-Legendre integration scheme considering the section responses at integration points of the element.

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). A compressive strength of 25MPa was considered for the SPEAR building and 16.7MPa for the Turkish buildings. The confinement effects provided by the lateral transverse reinforcement are taken into account through the rules proposed by Mander et al. (1988) whereby constant confining pressure is assumed throughout the entire stress-strain range.

The constitutive model used for the reinforcement steel was the one proposed by Menegotto and Pinto (1973) coupled with the isotropic hardening rules proposed by Filippou et al. (1983). The average yield strength of 360MPa was assumed for the SPEAR building and 371MPa for the Turkish five and eight storey buildings. Further details on the material properties of the Turkish buildings can be found in Bal et al. (2008).

Total translational masses in the three storey building amounted to 67.3ton each for first two floors and 62.8ton for the roof. The centre of mass is located at X=4.53m and Y=5.29m. In the five storey building, it was considered a mass of 263.41ton at each storey except in the last storey where the mass was 150.14ton. The centre of mass is located at X=9.7m and Y=4.9m. In the eight storey building it was considered a mass of 73ton in the first storey, a mass of 56ton in the last storey and mass of 65ton in the other storeys. The centre of mass is located at X= 3.83m and Y=6.49m.

Hysteretic damping was already implicitly included in the nonlinear fibre model formulation of the inelastic frame elements. In order to take into account for possible non-hysteretic sources of damping it was used a tangent stiffness-proportional damping (Priestley and Grant 2005). For the SPEAR building it was used a value of 2%, according to the experimental results at ISPRA, and for the Turkish buildings it was considered a 5% value.

SEISMIC ACTION

For the 3 storey SPEAR building, seven bi-directional semi-artificial ground motion records from the SPEAR project were considered. These records had been fitted to the Eurocode 8 (CEN 2004) elastic design spectrum (Type 1, soil C, η=1, S=1.15, β_0=0.02, T_B=0.2sec, T_C=0.6sec, T_D=2sec).

For the Turkish buildings, three bi-directional semi-artificial ground motion records were considered. These three are real records taken from the PEER's database website (PEER 2009). They were fitted to the Eurocode 8 elastic design spectrum (with the Turkish code features – Type 1, soil A, η=1, S=1, β_0=0.05, T_B=0.15sec, T_C=0.4sec, T_D=2sec) using the software RSPMatch2005 (Hancock et al. 2006). This software fits real records to a response spectrum defined by the user through the use of wavelets.

The nonlinear dynamic analyses were performed for four different orientations, on the three storey building, of aforementioned suit of seven semi-artificial ground motions, namely X+Y+, X+Y-, X-Y-, X-Y+, for a set of varying intensity of 0.05g, 0.1g, 0.2g and 0.3g. The median response among all the analyses, for each intensity level, was considered as the reference response of the building. For the nonlinear dynamic analyses of the Turkish buildings, 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 models, each one with five intensity levels for the 5 storey building (0.1g, 0.2g, 0.4g, 0.6g and 0.8g) and three intensity levels for the 8 storey building (0.1g, 0.2g and 0.4g). Once again, the median response among all the analyses for each intensity level was considered as the "true" response of the building.

The median response spectra of each set of ground motions were used to compute the nonlinear static procedures response.

PERFORMANCE OF THE PROPOSED METHODOLOGY

In this section, the results obtained with the Extended ACSM are presented and compared with the original ACSM, the CSM-FEMA440, the Extended N2 method and with the nonlinear dynamic analyses (NDA). The comparisons are presented in terms of lateral displacement profiles, interstorey drifts, chord rotation profiles, top displacement ratios and normalized top displacements. It is important to mention at this stage that the three storey building remains elastic or almost elastic for 0.05g and 0.lg, and it gets into the nonlinear regime for 0.2g and 0.3g (for which the building collapses). The five storey building remains elastic for 0.1g and 0.2g, and exhibits nonlinear behavior for 0.4g, 0.6g and 0.8g (for which the building collapses). The eight storey building remains elastic in the Y direction for all seismic intensities analysed, but in the X direction only for 0.1g. For 0.2g and 0.4g the building behaves inelastically. The building collapses for 0.4g due to a soft storey mechanism in the first storey along the X direction.

In (Pinho et al. 2008), a large parametric study was developed in order to evaluate the best damping formulas and the best spectral reduction factors to be applied in ACSM. Several combinations were tested on a large set of planar frame buildings and in a wide range of seismic intensities. From the obtained results it was clear that the damping dependent reduction factor proposed by Lin and Chang (2003) with the damping formulas proposed by Gulkan and Sozen (1974) were the ones that led the ACSM to the best results (closer to the nonlinear dynamic analyses) on the analysed structures. Therefore, these reduction factor and damping formulas were used in this paper in the original ACSM calculations.

Lateral displacement profiles

Comparisons of lateral displacement profiles between the proposed procedure and other NSPs are presented in Figures 7 and 8.

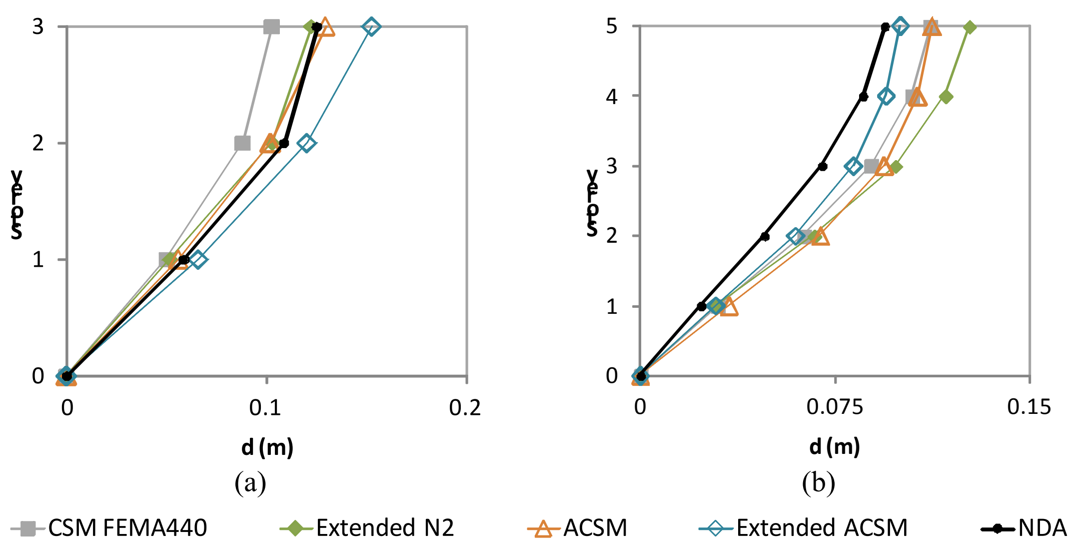


Figure 7. Lateral displacement profiles a) three storey building, column C2, X direction, 0.2g; b) five storey building, column S23, X direction, 0.4g.

In terms of lateral displacement profiles, one can observe in Figure 7a) that in the three storey building, the proposed Extended ACSM leads to better estimations than the CSM-FEMA440, especially on the edge columns. In fact, on the peripheral columns of this building the CSM-FEMA440 cannot reproduce the torsional motion, leading to underestimated displacement profiles. The Extended ACSM generally leads to responses very close to the nonlinear dynamic analyses, or slightly conservative. In this building, the

Extended N2 method and the ACSM also provide good estimations of the lateral displacement profiles. These conclusions are valid for all the seismic intensities analysed.

In Figure 7b) and 8a), one can observe that in the five storey building all the NSPs analysed lead to conservative results. However, the Extended ACSM is the one closer to the nonlinear dynamic response, especially in the upper floors.

The same conclusions can be drawn to the eight storey building, Figure 8b). In fact, all the methods analysed lead to conservative estimations, but once again the Extended ACSM gets closer to the nonlinear dynamic response.

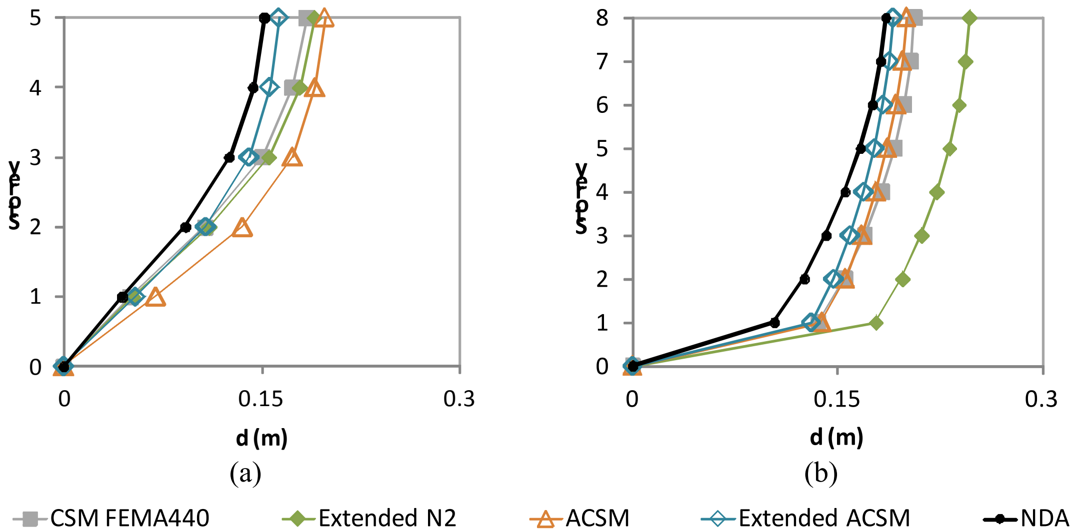


Figure 8. Lateral displacement profiles a) five storey building, column S14, X direction, 0.6g; b) eight storey building, column S23, X direction, 0.4g.

<u>Interstorey drifts and chord rotation profiles</u>

In Figures 9 and 10 are illustrated the comparisons between the proposed methodology and the other evaluated NSPs in terms of interstorey drifts and chord rotation profiles.

In terms of interstorey drift profiles, one can observe that the Extended ACSM is able to capture the response on the edges of the three storey building, Figure 9a). The other methods also lead to good estimations of the response but sometimes slightly under conservative: CSM-FEMA440 on the last floor and ACSM on the first floor.

In the eight storey building all methods overestimate the soft storey mechanism on the first floor, Figure 9b) and 10b). In the upper floors all methods lead to the same results practically matching the median nonlinear dynamic response.

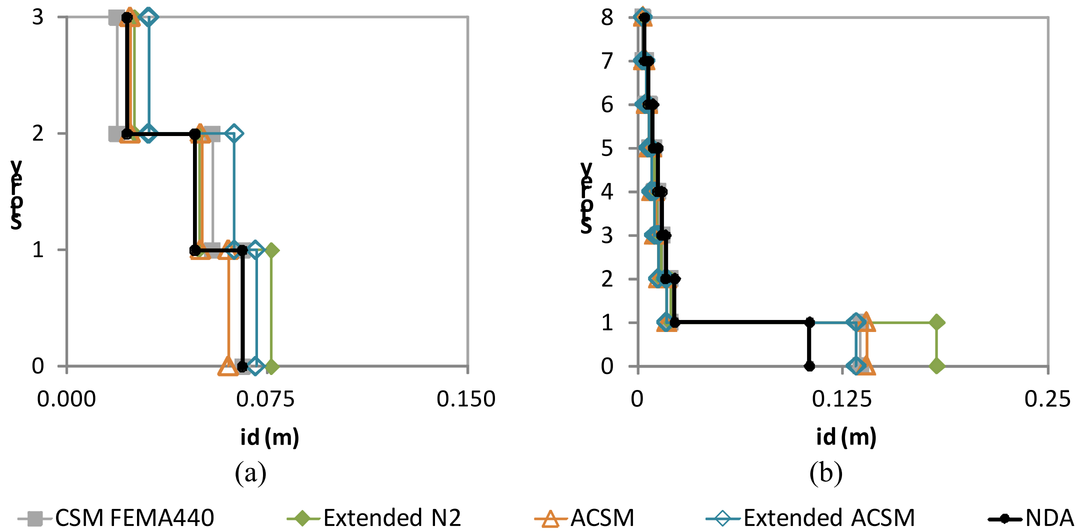


Figure 9. Interstorey drift profiles a) three storey building, column C2, Y direction, 0.3g; b) eight storey building, column S15, X direction, 0.4g.

In the five storey building, Figure 10a), the Extended ACSM matches the nonlinear dynamic results in the three upper storeys, leading to slightly conservative estimations of chord rotations on the first two storeys, but still close to the nonlinear dynamic profile. The original ACSM leads to approximately same results of the proposed procedure in the upper floors, but in the first two storeys it considerably overestimates the response. The other two methods lead to results close to the nonlinear dynamic analyses but slightly overestimated.

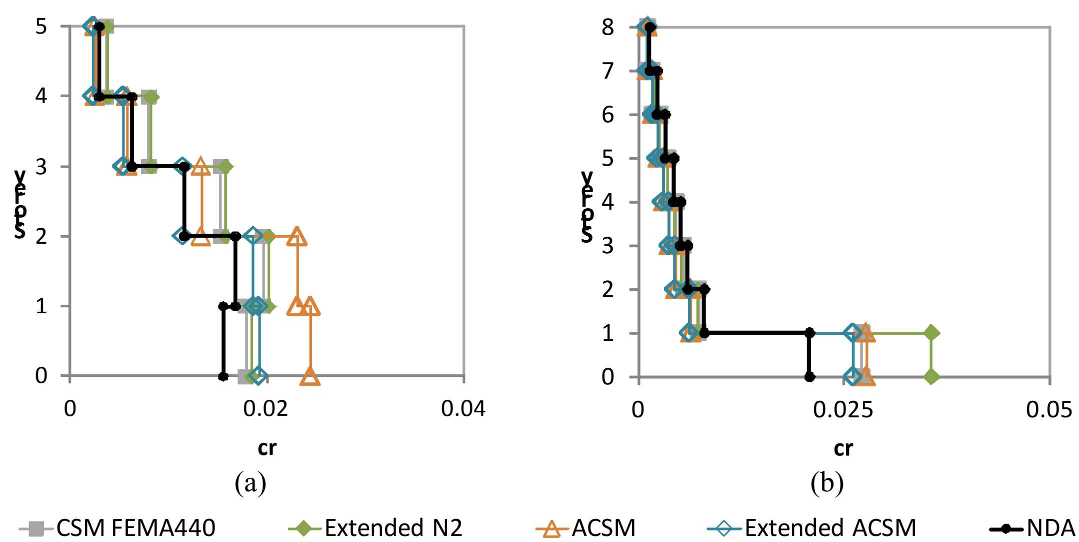


Figure 10. Chord rotations profiles a) five storey building, column S14, X direction, 0.6g; b) eight storey building, column S23, X direction, 0.4g.

Top displacement ratios

In order to get a quick overview of how the different NSPs perform, ratios of the values obtained with the latter for top displacement in different locations and the corresponding median estimates coming from the nonlinear dynamic analyses (equation 1) are computed.

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

The comparisons between the proposed method and the other NSPs in terms of top displacements ratios are plotted in Figures 11 and 12.

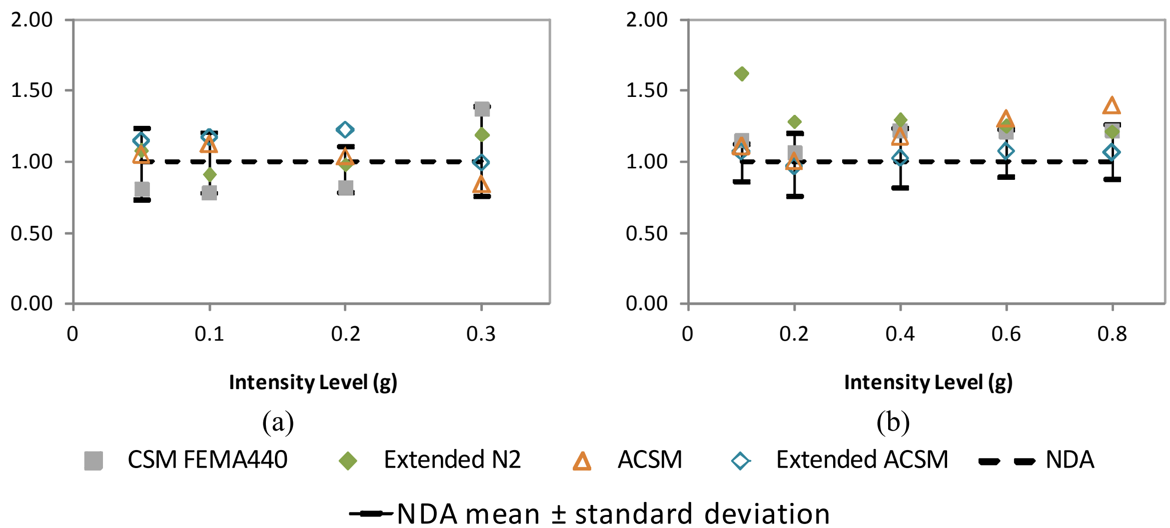


Figure 11. Top displacement ratios a) three storey building, column C2, X direction; b) five storey building, X direction, centre of mass.

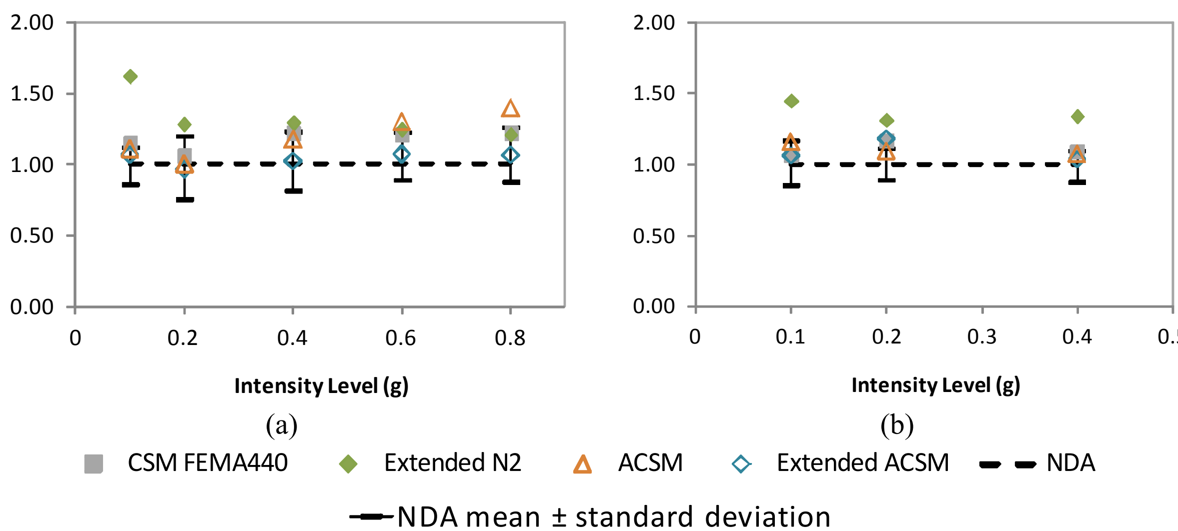


Figure 12. Top displacement ratios a) five storey building, X direction, column S13; b) eight storey building, X direction, column S9.

In terms of top displacement ratios, one can conclude that in the three storey building (Figure 11a)), the results on the edge columns are underestimated by the CSM-FEMA440 and well estimated by the proposed procedure. The other two methods also lead to good results, except the ACSM that underestimates the top displacement for 0.3g.

In the five storey building, Figure 11b) and 12a), one can observe that the ACSM, the CSM-FEMA440 and the Extended ACSM perfectly match the nonlinear dynamic results for lower levels of seismic intensity (elastic regime). However, for higher levels of inelasticity, the proposed procedure maintains the good matching with the nonlinear dynamic results while the original ACSM and the CSM-FEMA440 overestimate the response. This overestimation in the inelastic regime gets higher as the seismic intensity increases, i.e. as the structure increases its level of nonlinear behavior. The Extended N2 method usually leads to conservative results through all the seismic intensities tested. Note that this conservativeness is higher in the elastic range (example: 0.1g in the five storey building, Figure 11b) and 12a)).

In the eight storey building, all methods seem to provide conservative results, Figure 12b).

Normalized top displacements

In Figures 13 and 14 are plotted the normalized top displacements in the three case studies evaluated, for the Extended ACSM and for the other NSPs. This measure is obtained by normalizing the edge displacement values with respect to those of the centre of mass, and it reflects the torsional behavior of the structure (Fajfar et al. 2005b)).

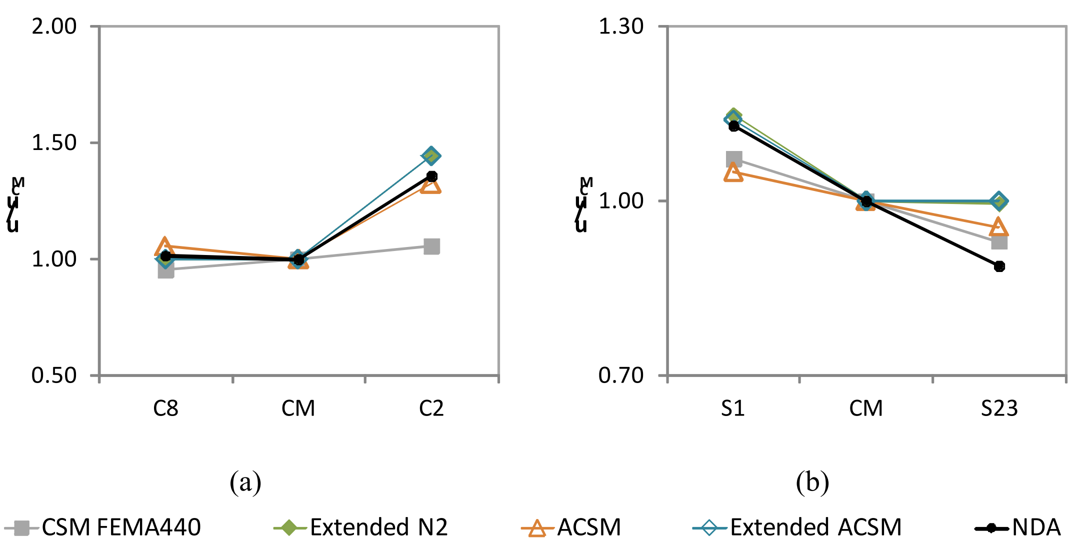


Figure 13. Normalized top displacements, X direction: a) three storey building, 0.1g; b) five storey building, 0.2g.

In terms of normalized top displacements one can observe that the Extended ACSM and the Extended N2 are able to reproduce the torsional motion of the buildings in a very good fashion, due to the use of torsional correction factors. These methods are able to capture the torsional amplification on the flexible edge, and they usually overestimate or reproduce in an exact way the response on the stiff edge. These correction factors do not consider any de-amplification of displacements due to torsion, as it was previously explained, therefore the response on the stiff edge is invariantly overestimated. This conservativeness is quite acceptable in terms of seismic assessment.

The other NSPs estimate the torsional motion of the buildings linearly from one side of the building to the other, usually underestimating one of the edges. The original ACSM provided good results in the three storey building, but it could not keep the god performance in the other two case studies.

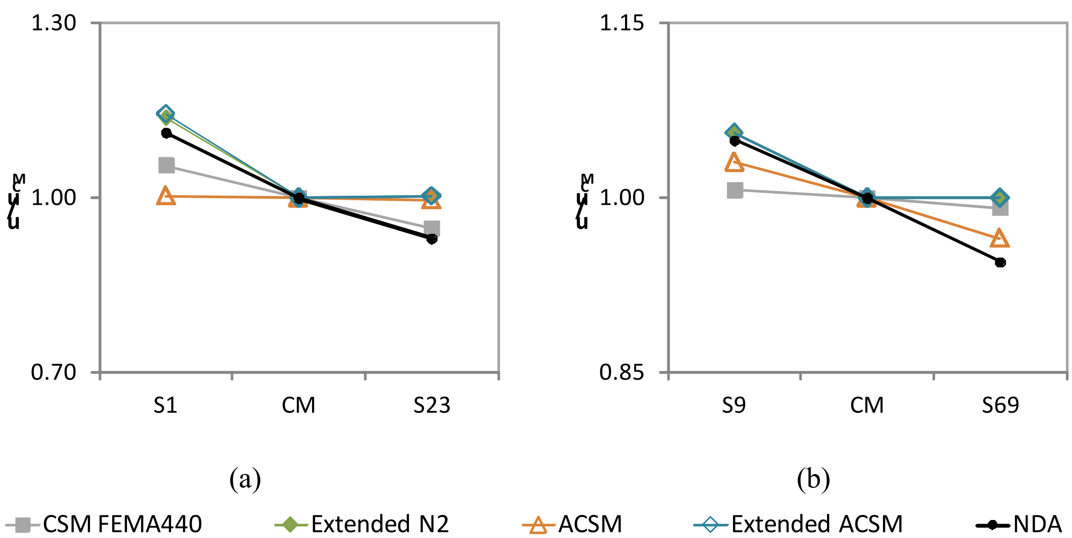


Figure 14. Normalized top displacements, X direction: a) five storey building, 0.6g; b) eight storey building, 0.4g.

Figure 15 presents a comparison between the normalized roof displacements obtained with the ACSM with the reduction factor proposed by Lin and Chang and the damping formulas proposed by Gulkan and Sozen (ACSM LC GS), the ACSM with the equations of FEMA440 (ACSM FEMA440), the Extended ACSM and the nonlinear dynamic analyses (NDA).

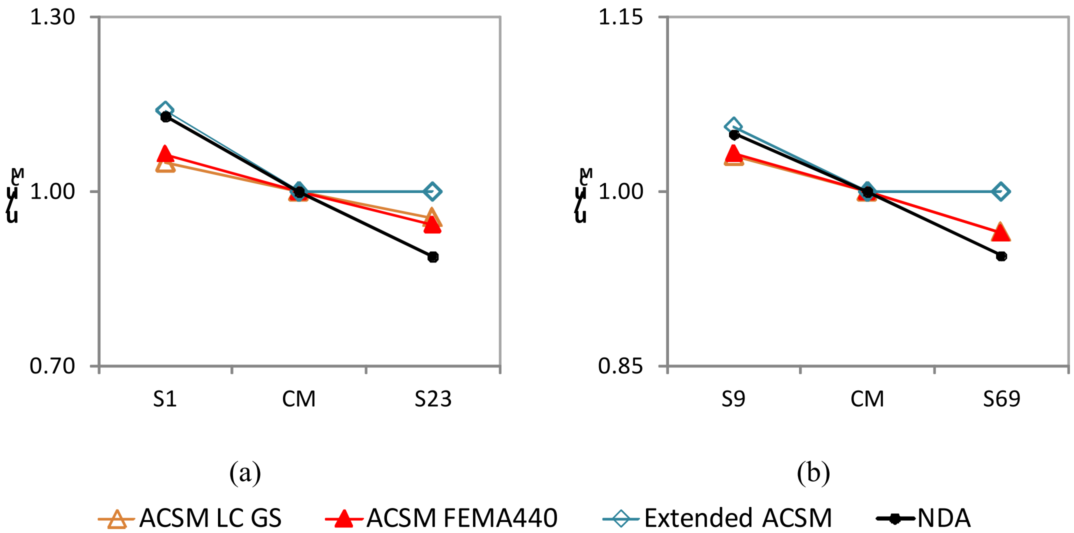


Figure 15. Normalized top displacements, X direction: a) five storey building, 0.2g; b) eight storey building, 0.4g.

From the plots one can conclude that both ACSM LC GS and ACSM FEMA440 lead to similar results, although overestimating the response on the flexible edge of the buildings. So, the use of FEMA440 equations in ACSM is not enough to obtain good results. This fact corroborates the need of using torsional correction factors in the proposed Extended ACSM. This procedure is able to correctly estimate the response on the flexible edge overestimating the results on the stiff side. These conclusions were also observed in the other measures analyzed.

THE ADVANTAGES OF THE EXTENDED ACSM

The Extended ACSM herein proposed seems to exhibit a satisfactory performance on the seismic assessment of the three plan irregular buildings analysed, through all the seismic intensities tested. The justification relies on the fact that the procedure comprises the best features of some of the most commonly used NSPs – ACSM, CSM-FEMA440 and Extended N2 method.

DAP analysis

The proposed methodology uses a displacement based adaptive pushover (DAP) that updates the load pattern to be applied in each step, based on the modal properties of the structure on that step of the analysis. Therefore, the method takes into account the stiffness degradation, the period elongation and the progressive structural damage. The other methods herein evaluated (except the ACSM), use a conventional force based non-adaptive pushover, i.e. the incremental load to be applied in the structure maintains the same pattern. For this reason, the referred methods are not able to reproduce the structural specificities mentioned in the DAP case.

The CSM-FEMA440 and the Extended N2 method use a force based load pattern proportional to the mass and to the elastic first mode of vibration of the structure in the direction under analysis. Therefore, none of the methods takes into account the contribution of the higher modes. The DAP used in the ACSM and in the proposed methodology, builds the displacement pattern to be applied in each step of the analysis considering the contribution of a pre-defined number of modes of vibration calculated based on the actual structural stiffness of that step. Therefore, the method takes into account the contribution of the higher modes of vibration of the structure. This is clear in the five and eight storey buildings, where the method led to more accurate results in the upper floors in terms of lateral displacements than the procedures that use conventional pushovers. An extension of the N2 method to take into account higher mode effects was recently proposed by Kreslin and Fajfar (2011).

By using DAP, the proposed methodology is able to capture in a more accurate fashion the response profiles, namely in terms of lateral displacements, interstorey drifts and chord rotations.

MDOF to SDOF transformation

For the definition of the SDOF capacity curve, the CSM-FEMA440 and the Extended N2 method consider only one single control node – usually the centre of mass of the last floor, thus not contributing to a correct estimation of the structural torsional response.

On the other hand, the ACSM and the methodology herein proposed compute the SDOF capacity curve taking into account all beam-column and beam-beam nodes of the structure, therefore the torsional response can be better reproduced.

Target displacement calculation

In the Extended ACSM, in CSM-FEMA440 and in ACSM the target displacement is calculated intersecting the SDOF capacity curve with the reduced ADRS spectrum. The Extended ACSM uses the algorithm presented in FEMA440 for the computation of the effective period, effective damping and spectral reduction factor. It also uses the modified acceleration-displacement response spectrum (MADRS), introduced in this guideline. As it was concluded in (Bhatt and Bento 2011), this new algorithm leads to better estimations of the damping than the one used in ATC40. As it was mentioned before, the reduction factor and the damping estimation formulas used in the original ACSM calculations were the ones proposed by Lin and Chang and by Gulkan and Sozen respectively.

Table 1. Three storey building - effective damping ratios (%).

	Three storey building: 2% viscous damping					
	Extended ACSM		CSM-FEMA440		ACSM	
Intensity level (g)	X	Y	X	Y	X	Y
0.05g	2.2	2.1	2.1	2.1	3.5	3.8
0.1g	3.0	2.5	2.2	2.1	5.2	4.4
0.2g	9.7	6.4	5.8	3.2	11.9	9.8

Tables 1, 2 and 3 show the damping ratios calculated by the three methods in all case studies. It is important to mention that the Extended ACSM and the CSM-FEMA440 lead to similar estimations of the damping in the elastic range for the three buildings analysed. In the analysed buildings, one can observe that in the elastic and near elastic range - 0.05g and 0.1g for the three storey building, 0.1g and 0.2g for the five storey building, 0.1g for the eight storey building - both methods lead to similar estimations of the viscous damping used in the nonlinear dynamic analyses – 2% in the three storey building and 5% in the five and eight storey buildings. This fact is justified by the accuracy of the formulas proposed in FEMA440 and used by both methods, and because both adaptive and conventional pushover curves are very similar in the elastic range.

Table 2. Five storey building - effective damping ratios (%).

	Five storey building: 5% viscous damping					
	Extended ACSM		CSM-FEMA440		ACSM	
Intensity level (g)	X	Y	X	Y	X	Y
0.1g	5.1	5.1	5.2	5.4	6.5	6.8
0.2g	5.3	5.2	5.3	5.3	7.3	7.0
0.4g	7.2	6.5	6.7	6.4	10.2	9.3
0.6g	12.5	8.8	10.9	10.0	14.0	11.8

Table 3. Eight storey building - effective damping ratios (%).

	Eight storey building: 5% viscous damping		
	Extended ACSM	CSM-FEMA440	ACSM
Intensity level (g)	X	X	X
0.1g	5.3	5.3	7.3
0.2g	5.5	5.4	7.7
0.4g	8.8	9.2	12.3

In the inelastic range, the Extended ACSM leads in general to slightly larger estimations of the damping than the CSM-FEMA440. Notwithstanding both methods use the same formulas for the damping calculation, the differences on the damping values obtained in the inelastic range are due to the differences between the adaptive and conventional pushover curves used by each method, and based on which the damping is calculated. Since the results of the Extended ACSM are closer to the nonlinear dynamic analyses than the ones obtained with the CSM-FEMA440 in the inelastic range (especially in the columns near the centre of mass of the buildings where the torsional effects are not significant and therefore the comparison between the methods is not influenced by the torsional correction factors), one can conclude that the damping estimations in the inelastic regime obtained with the proposed methodology seem to be more realistic. Since the two curves (adaptive and conventional) are very similar in the elastic or almost elastic regime for each building, the damping ratios computed by both methods are also very similar in this range.

Even though the damping estimations of the ACSM are larger, the results obtained by this method seem to be more conservative than the ones obtained with the proposed procedure. Since both methods use a DAP capacity curve, this difference can be explained due to the different reduction factors used by each method.

The Extended N2 method uses the equal displacement rule for the calculation of the target displacement, which can explain the conservative results obtained in some cases. The conservativeness of the Extended N2 method increases in the elastic range. In fact, according to Fajfar the method was not developed for the elastic regime. In this work the results obtained with the optional iterative procedure proposed in EC8 were not presented. The results in the inelastic regime using both recommended and optional procedure are quite similar. However, in the elastic regime the results of the iterative procedure are less conservative than the ones obtained with the recommended method.

Torsional correction factors

Only the Extended N2 method and the proposed methodology, use correction factors in order to take into account the torsional effects. These correction factors based on Pushover and linear elastic analyses, proved to estimate in a good fashion the torsional motion of plan irregular buildings. In fact, the only NSPs that were able to reproduce in a correct or conservative fashion the normalized top displacements were the ones that use these correction factors. The other NSPs generally underestimated the normalized top displacements in one of the edges of the analysed buildings.

By using torsional correction factors, the Extended ACSM leads to satisfactory estimations of the torsional motion of the buildings. As an example, the response on both flexible and stiff edges of the three storey building in terms of lateral displacement, interstorey drifts, chord rotations profiles and top displacement ratios, is reproduced in an accurate fashion by the method. On the other hand, the CSM-FEMA440 usually underestimates the response on these edges, through all the seismic intensities tested.

In terms of normalized top displacements, the proposed method was able to capture the torsional amplification on the flexible edges and it usually overestimated the response on the stiff edges of the three analysed buildings. The CSM-FEMA440 and the ACSM generally estimated in a linear way the response from one side of the building to the other, underestimating one of the edges. These conclusions were observed for all the seismic intensities tested.

CONCLUSIONS

In this paper, an extended version of the ACSM is proposed for the seismic assessment of plan irregular buildings, combining the most efficient and accurate features of some of the most commonly used NPSs.

The method was tested in three existing buildings asymmetric in plan, for several seismic intensities and compared with the original CSM-FEMA440, the ACSM, the Extended N2 method and with the most exact nonlinear dynamic analyses.

The satisfactory results obtained with the proposed methodology can be justified due to the following reasons:

1) The method uses a displacement based adaptive pushover (DAP);
2) For the SDOF capacity curve definition, the procedure calculates the equivalent SDOF structural displacement based on the current deformed pattern. This concept can be useful in the 3D case;
3) The computation of the target displacement is made using the algorithm proposed in FEMA440 for the calculation of the effective period, damping, reduction factor and the new MADRS;
4) In order to take into account the torsional effects, the Extended ACSM uses correction factors, as proposed in the Extended N2 method.

In terms of normalized top displacements, which clearly illustrate the torsional motion of the structures, one could conclude that the CSM-FEMA440 and the ACSM generally underestimated the response in one of the edges of the buildings. On the other hand, the Extended N2 method and the Extended ACSM could reproduce in a correct fashion the torsional motion of the case studies.

In terms of lateral displacement profiles, interstorey drifts, chord rotations and top displacement ratios one can conclude that the Extended ACSM leads to results close to the nonlinear dynamic analyses, but always on the conservative side.

Despite both methods use the DAP and the same MDOF to SDOF transformation, the Extended ACSM leads to results closer to the nonlinear dynamic analyses than the ACSM. In terms of normalized top displacements, the proposed method provides better results than the ACSM due to the use of torsional correction factors.

These conclusions were taken for all the seismic intensities tested and consequently for different stages of structural inelasticity of each building.

The methods evaluated in this paper have different levels of complexity. To what simplified methods are concerned, accuracy and complexity are important issues. The authors believe that if the procedure proposed herein is programmed in a software package, it turns automatic and very easy to be performed. However, it is of extreme importance that users perfectly understand the theoretical background of the analyses. It can turn very dangerous to use analysis software as a black box, and may lead to wrong results.

The results herein obtained with the analysed structures, seem optimistic regarding the use of the proposed procedure on the seismic assessment of plan asymmetric buildings.

Further tests in buildings with other typologies should be carried out in order to take definitive conclusions.

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