4th European Workshop on the *Seismic Behaviour of Irregular and Complex Structures*
Thessaloniki, Greece, 26–27 August 2005

A DISPLACEMENT-BASED ADAPTIVE PUSHOVER ALGORITHM FOR ASSESSMENT OF VERTICALLY IRREGULAR FRAMES

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ABSTRACT

Due to the unvarying nature of the applied displacement loading vector, conventional (non-adaptive) displacement-based pushover analysis can conceal important structural characteristics, such as strength irregularities and soft storeys, should the displacement pattern adopted at the start of the analysis not correspond to the structure's post-yield failure mechanism. Consequently, when only non-adaptive static nonlinear analysis tools are available, as has been the case throughout the past, force-based pushover does constitute a preferable choice over its displacement-based counterpart. On the other hand, however, if one is able to apply displacements, rather than forces, in an adaptive fashion, that is, with the possibility of updating the displacement loading pattern according to the structural properties of the model at each step of the analysis, then a conceptually appealing deformation-based nonlinear static analysis tool would be obtained. The present study focuses therefore on the verification of the accuracy of such an innovative displacement-based adaptive pushover method (DAP), to estimate the response characteristics of vertically irregular frames subjected to earthquake excitation.

INTRODUCTION

A major challenge in performance-based engineering is to develop simple, yet accurate methods for estimating seismic demand on structures considering their inelastic behaviour: the use of nonlinear static procedures, or pushover analyses, is inevitably going to be favoured over complex, impractical for widespread professional use, nonlinear time-history methods. The term 'pushover analysis' describes a modern variation of the classical 'collapse analysis' method, as fittingly described by Kunnath [1]. The procedure consists of an incremental-iterative solution of the static equilibrium equations corresponding to a nonlinear structural model subjected to a monotonically increasing lateral load pattern. The structural resistance is evaluated and the stiffness matrix is updated at each increment of the forcing function, up to convergence. The solution proceeds until (i) a predefined performance limit state is reached, (ii) structural collapse is incipient or (iii) the program fails to converge.

Within the framework of earthquake engineering, pushover analysis is employed with the objective of deriving, with relative ease, an envelope of the response parameters that would otherwise be obtained through a much more complex and time-consuming Incremental Dynamic Analysis (IDA) procedure, as can be construed by Figure 1. IDA is a parametric analysis method by which a structure is subjected to a series of nonlinear time-history analyses of increasing intensity [2], with the objective of attaining an accurate indication of the "true" dynamic response of a structure subjected to earthquake action.

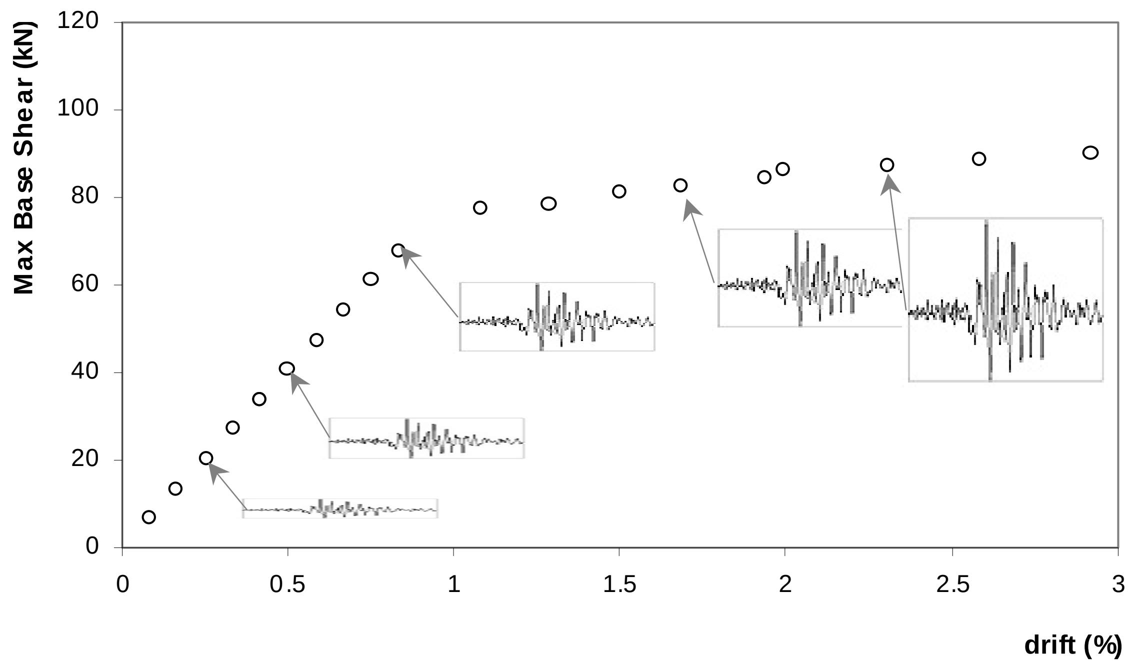


Figure 1: Maximum base-shear and top displacement values obtained with incremental dynamic analysis.

In tandem with the present drive for performance-based seismic engineering, there is also a push for the development and code implementation of displacement or, more generally, deformation-based design and assessment methods. Therefore, it would seem that applying displacement loading, rather than force actions, in pushover procedures would be an appropriate option for nonlinear static analysis of structures subjected to earthquake action. However, due to the unvarying nature of the applied displacement loading vector, conventional (non-adaptive) displacement-based pushover analysis can conceal important structural characteristics, such as strength irregularities and soft storeys, should the displacement pattern adopted at the start of the analysis not correspond to the structure's post-yield failure mechanism. Consequently, when only non-adaptive static nonlinear analysis tools are available, as has been the case throughout the past, force-based pushover does constitute a preferable choice over its displacement-based counterpart.

On the other hand, however, if one is able to apply displacements, rather than forces, in an adaptive fashion, that is, with the possibility of updating the displacement loading pattern according to the structural properties of the model at each step of the analysis, then a conceptually appealing deformation-based nonlinear static analysis tool would be obtained. The present study focuses therefore on the verification of the accuracy of such an innovative displacement-based adaptive pushover method (DAP), to estimate the response characteristics of vertically irregular frames subjected to earthquake excitation. A series of DAP and conventional pushover analyses is carried out and compared, in terms of both global and local response, with the predictions of inelastic dynamic analysis, employing two representative 2D building models featuring irregular type of response. It is shown that the new approach yields response predictions that are superior to those obtained by its force-based counterparts. In addition, the innovative algorithm proves to be numerically stable, even in the highly inelastic region, whereas the additional modelling and computational effort, with respect to conventional pushover procedures, is negligible.

NONLINEAR STATIC PUSHOVER IN CURRENT PRACTICE

According to recently introduced code provisions, such as FEMA-356 [3] and Eurocode 8 [4], pushover analysis should consist of subjecting the structure to an increasing vector of horizontal forces with invariant pattern. Both the force distribution and target displacement are based on the assumptions that the response is controlled by the fundamental mode and the mode shape remains unchanged until collapse occurs. Two lateral load patterns, namely the first mode proportional and the uniform, are recommended to approximately bound the likely distribution of the inertia forces in the elastic and inelastic range, respectively.

However, a number of recent studies, summarised in the FEMA-440 report [5], raise doubts on the effectiveness of these conventional force-based pushover methods in estimating the seismic demand throughout the full deformation range: (i) inaccurate prediction of deformations when higher modes are important and/or the structure is highly pushed into its nonlinear post-yield range, (ii) inaccurate prediction of local damage concentrations, responsible for changing the modal response, (iii) inability of reproducing peculiar dynamic effects, neglecting sources of energy dissipation such as kinetic energy, viscous damping, and duration effects, (iv) difficulty in incorporating three-dimensional and cyclic earthquake loading effects.

Below, in Figures 2 and 3, examples of inadequate prediction of both the capacity curve as well as the deformation response characteristics of a 12-storey reinforced concrete frame subjected to a natural earthquake recording (case-study RM15-NR2 in [6]) and of a 4-storey irregular frame subjected to an artificial accelerogram (ICONS full-scale test specimen, described in [7]) are given. It is noted that although the 12-storey building is regular in height, its response is heavily influenced by higher mode effects, effectively rendering its seismic behaviour highly irregular in height, as conspicuously shown by Figure 2a. The standard pushover results have been carried out using both triangular and uniform loading distributions, and are compared with the envelope of results obtained with incremental dynamic analysis.

RECENT DEVELOPMENTS IN PUSHOVER ANALYSIS

In an attempt to include higher modes effects, a number of Multi-Modal Inelastic Procedures (MMP) has been recently developed. These may be referred to as “pushover-based

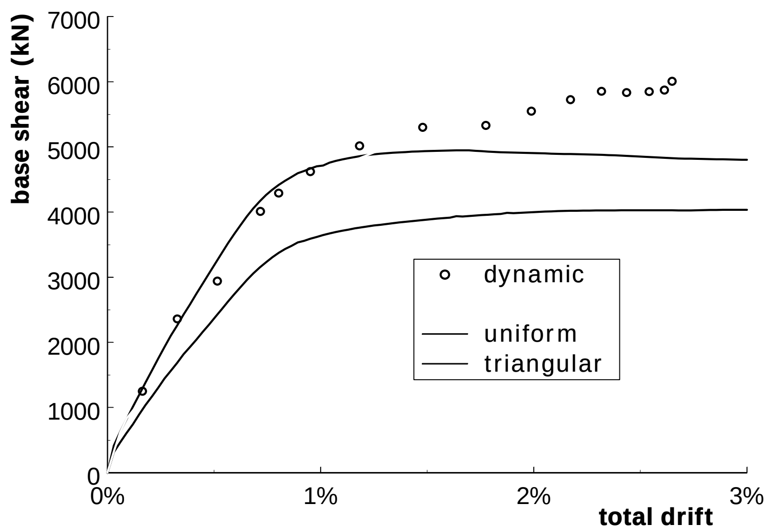


Figure 2: Capacity curves of a 12-storey building, obtained with standard pushover.

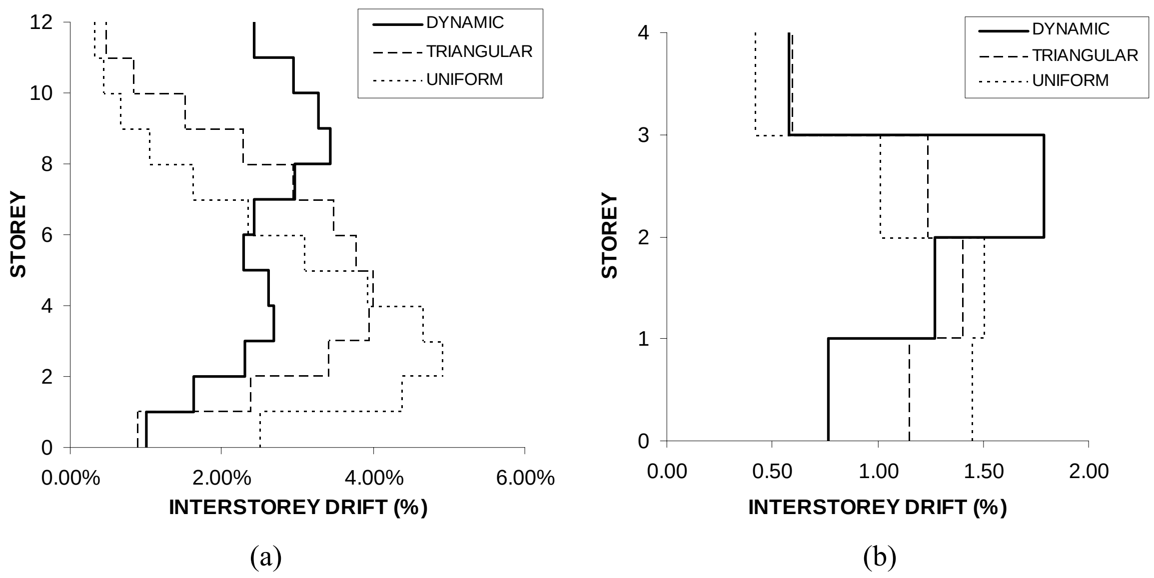


Figure 3: Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with standard pushover.

procedures", as opposed to "pure pushover" analysis methods, since they estimate the seismic demand at one or more specific seismic levels (i.e. "individual point" on the pushover curve) rather than providing a structural capacity curve throughout the whole deformation range. Such methods essentially consist in performing conventional pushover analyses per each mode separately and then estimating the structural response by combining the action effects derived from each of the modal responses (alternatively, the "most critical mode" may be considered in isolation). Paret *et al.* [8] first suggested the Multi-Modal Pushover procedure, which was then refined by Moghadam and Tso [9]. Chopra and Goel [10], on the other hand, have developed and proposed a Modal Pushover Analysis (MPA) technique, which Hernández-Montes *et al.* [11] have then adapted into an Energy-based Pushover formulation.

Although the aforementioned methods constitute a significant improvement over traditional pushover techniques, they still do not account for the effect that damage accumulation, induced by the increasing deformation levels imposed on the structure, has on the response of the latter. Cumulative material straining introduces a reduction in stiffness which, in turn, causes an elongation of the periods of vibration (Figure 4), which then, depending on the shape of the response spectrum being considered (or on the frequency content of the input record being employed), may trigger significant changes in the response characteristics of the buildings (Figure 5).

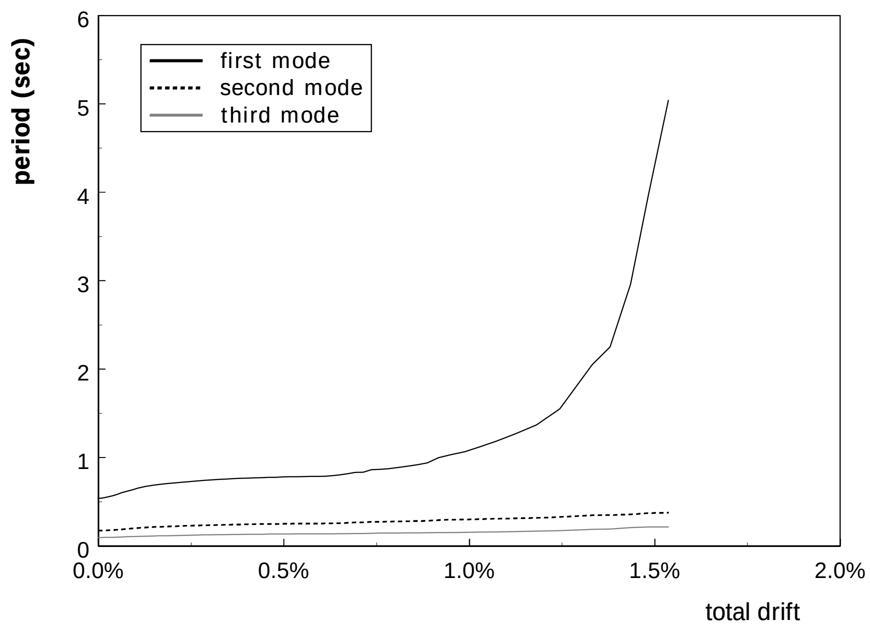


Figure 4: Periods of vibration of 4-storey building under increasing levels of deformation.

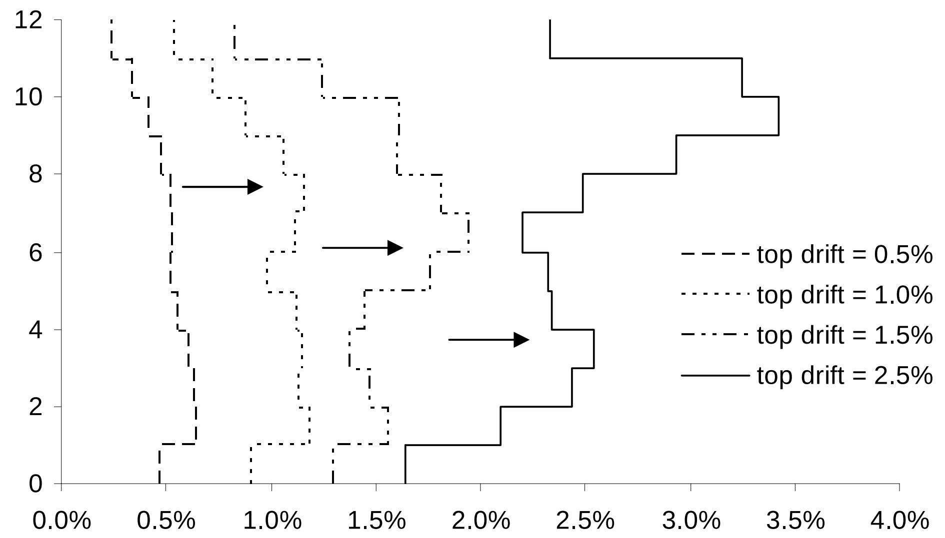


Figure 5: Interstorey drift profiles of a 12-storey building subjected to increasing levels of deformation.

Krawinkler and Seneviratna [12] summarised the above with a single statement; fixed load patterns in pushover analysis are limiting, be they first modal or multimodal derived, because no fixed distribution is able of representing the dynamic response throughout the full deformation range. As a result, recent years have witnessed the development and introduction of so-called Adaptive Pushover methods whereby the loading vector is updated at each analysis step, reflecting the progressive stiffness degradation of the structure induced by the penetration in the inelastic range (Figure 6). These methods, some variations of which are also termed as incremental response spectrum analysis [13], can evidently consider the effects of the higher modes and of the input frequency content.

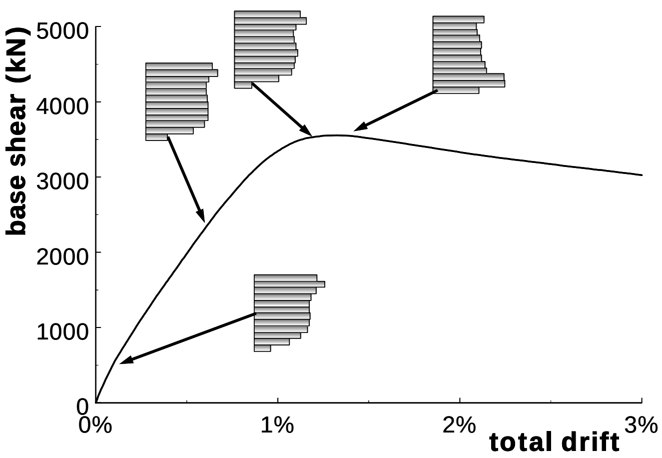
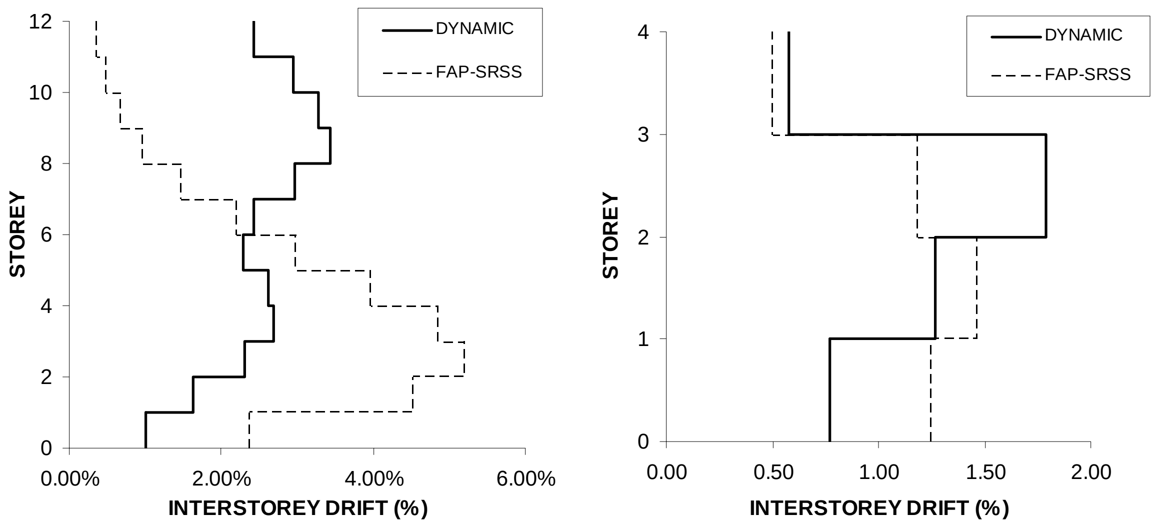


Figure 6: Adaptive pushover: shape of loading vector is updated at each analysis step.

Adaptive procedures have been proposed by Bracci *et al.* [14], Sasaki *et al.* [15], Satyarno *et al.* [16], Matsumori *et al.* [17], Gupta and Kunnath [18], Requena and Ayala [19], Elnashai [20], Antoniou *et al.* [21], Aydinoglu [13]. The methodologies elaborated by the latter four researchers are conceptually identical, with the difference that [20] and [21] implemented the procedure within a fibre analysis framework, allowing for a continuous, rather than discrete, force distribution update to be carried out. These adaptive procedures have led to an improvement in the agreement between static and dynamic analysis results, thanks to the consideration of: (i) spectrum scaling, (ii) higher modes contributions, (iii) alteration of local resistance and modal characteristics induced by the accumulated damage, (iv) load updating according to the eigen-solutions from instantaneous nonlinear stiffness and mass matrix.

However, despite such apparent conceptual superiority, or at least despite its conspicuously more elaborated formulation, the improvement introduced by current Force-based Adaptive Pushover (FAP) procedures is not-necessarily impressive, with respect to its traditional non-adaptive counterparts, particularly in what concerns the estimation of deformation patterns of buildings, which are poorly predicted by both types of analysis, as shown in Figure 7. As described by Kunnath [1] and López-Menjivar [22], the main reason for such underperformance seems to be the quadratic modal combination rules (SRSS, CQC) used in computing the adaptive updating of the load vector; these rules will inevitably lead to monotonically increasing load vectors, since the possibility of sign change in applied loads at any location is precluded, whilst it may be needed to represent the uneven redistribution of forces after an inelastic mechanism is triggered at some location.



(a) (b)

Figure 7: Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with Force-based Adaptive Pushover using SRSS modal combination.

With the above in mind, Kunnath [1] and López-Menjivar [22] have proposed an alternative modal combination scheme, consisting of a weighted Direct Vectorial Addition (DVA) of the different modal shapes that can be mathematically expressed as:

$$F_i = \sum_{j=1}^{n} \alpha_j \Gamma_j \phi_{j,i} M_j Sa_j \qquad (1)$$

where i is the storey number, j is the mode number, n is the highest mode of interest, Γ_j is the modal participation factor for the j^{th} mode, $\phi_{i,j}$ is the mass normalised mode shape value for the i^{th} storey and the j^{th} mode, M_i is the mass of the i^{th} storey and Sa_j represents the acceleration response spectrum ordinate corresponding to the period of vibration of the j^{th} mode. Finally, α_j is a weighting factor that aims at accounting for the varying relative importance that each mode j has on the maximum response of the structure.

The employment of such alternative modal combination procedure, may indeed lead to the attainment of improved results, as demonstrated by the interstorey drift profiles given in Figure 8, obtained through consideration of the first three modes of vibration of the buildings, and using α_1=1.0, α_2=-1.0 and α_3 =-1.0 in Equation (1). However, the arbitrary nature of these weighting factors α_j renders the method unfeasible for practical application, as explicitly acknowledged in [1] and demonstrated in [22]. Indeed, in the latter work it is demonstrated how values of α_j that lead to optimum results for some building configurations, lead then to poor predictions in buildings with diverse characteristics. Therefore, and until a general procedure to correctly determine the values of the weighting factors is found, the DVA adaptive pushover modality cannot really be deemed as a valid solution for practical application.

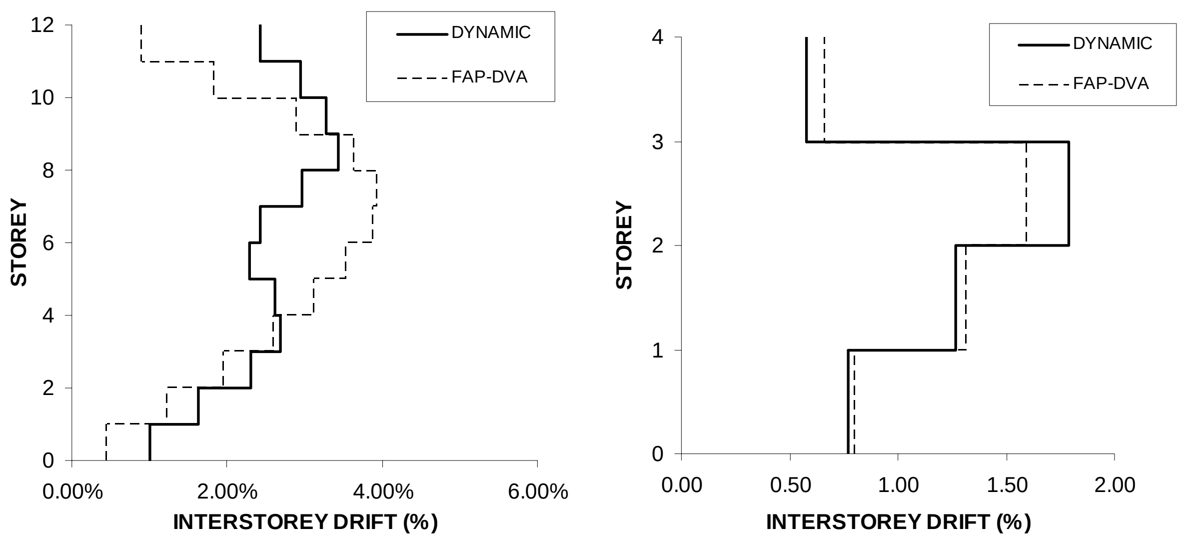


Figure 8: Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with Force-based Adaptive Pushover using DVA modal combination.

DISPLACEMENT-BASED ADAPTIVE PUSHOVER (DAP)

With a view to overcome the limitations described above, Antoniou and Pinho [23] have proposed a paradigm shift in pushover analysis, by introducing the innovative concept of Displacement-based Adaptive Pushover (DAP). Contrarily to what happens in non-adaptive pushover, where the application of a constant displacement profile would force a predetermined and possibly inappropriate response mode, thus concealing important structural characteristics and concentrated inelastic mechanisms at a given location, within an adaptive framework, a displacement-based pushover is entirely feasible, since the loading vector is updated at each step of the analysis according to the current dynamic characteristics of the structure.

It is worth recalling, or re-iterating, that in adaptive pushover the response of the structure is computed in incremental fashion, through piecewise linearisation, as schematically shown in Figure 9, below. Therefore, it is possible to use the tangent stiffness at the start of each increment, together with the mass of the system, to compute modal response characteristics of each incremental pseudo-system through elastic eigenvalue analysis, and use such modal quantities to congruently update (i.e. increment) the pushover loading vector. Aydinoglu [13] eloquently described such process by naming this type of analysis as Incremental Response Spectrum Analysis (IRSA), a nomenclature that despite not being adopted by the authors of this paper is nonetheless fully endorsed.

DAP – Methodology

The implementation of DAP can be structured in four main stages; (i) definition of the nominal load vector and inertia mass, (ii) computation of the load factor, (iii) calculation of the normalised scaling vector and (iv) updating of the loading displacement vector. Whilst the first step is carried out only once, at the start of the analysis, its three remaining counterparts are repeated at every equilibrium stage of the nonlinear static analysis procedure, as described in the following subsections.

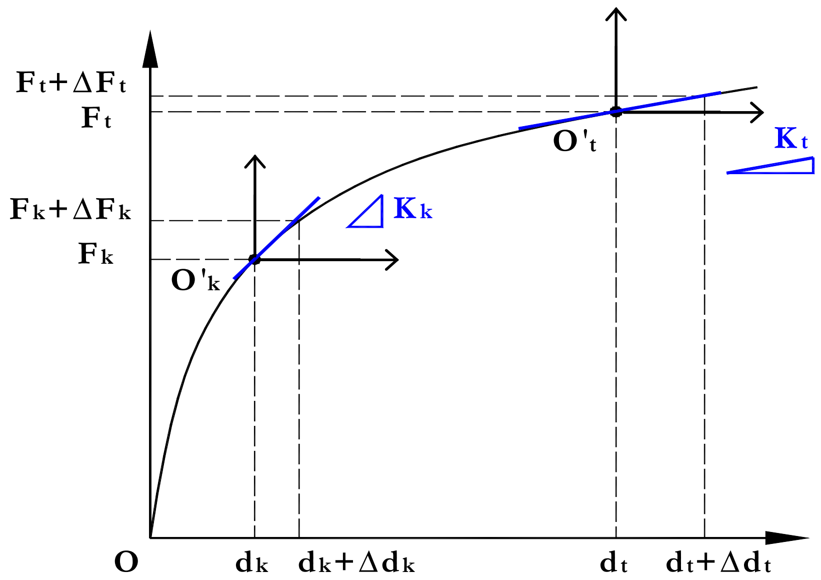


Figure 9: The use of tangent stiffness in updating (i.e. incrementing) the loading vector.

The loading vector shape is automatically defined and updated by the solution algorithm at each analysis step, for which reason the nominal vector of displacements, U_0, must always feature a uniform (rectangular) distribution shape, in height, so as not to distort the load vector configuration determined in correspondence to the dynamic response characteristics of the structure at each analysis step. In addition, it is noteworthy that the adaptive pushover requires the inertia mass *M* of the structure to be modelled, so that the eigenvalue analysis, employed in updating the load vector shape, may be carried out.

The magnitude of the load vector *U* at any given analysis step is given by the product of its nominal counterpart U_0, defined above, and the load factor λ at that step (see Equation 2). The latter is automatically increased, by means of a load control strategy [6], until a predefined analysis target, or numerical failure, is reached.

$$U = \lambda \cdot U_0 \tag{2}$$

The normalized modal scaling vector, $\overline{D}$, used to determine the shape of the load vector (or load increment vector) at each step, is computed at the start of each load increment. In order for such scaling vector to reflect the actual stiffness state of the structure, as obtained at the end of the previous load increment, an eigenvalue analysis is carried out. To this end, the Lanczos algorithm [24] is employed to determine the modal shape and participation factors of any given predefined number of modes. Modal loads can be combined by using either the Square Root of the Sum of the Squares (SRSS) or the Complete Quadratic Combination (CQC) methods.

Since application to the analysis of buildings is the scope of the present work, use is made of the interstorey drift-based scaling algorithm, whereby maximum interstorey drift values obtained directly from modal analysis, rather than from the difference between not-necessarily simultaneous maximum floor displacement values, are used to compute the scaling displacement vector. This comes as a reflection of the fact that the maximum displacement of a particular floor level, being essentially the relative displacement between that floor and the ground, provides insufficient insight into the actual level of damage incurred by buildings subject to earthquake loading. On the contrary, interstorey drifts, obtained as the difference between floor displacements at two consecutive levels, feature a much clearer and direct relationship to horizontal deformation demand on buildings. Readers are referred to [25] for further details on this formulation.

In such an interstorey drift-based scaling technique, the eigenvalue vectors are thus employed to determine the interstorey drifts for each mode Δ_{ij}, as shown in Equation (3), while the displacement pattern D_i at the i^{th} storey is obtained through the summation of the modal-combined inter-storey drifts of the storeys below that level, i.e. drifts Δ_1 to Δ_i:

$$D_i = \sum_{k=1}^{i} \Delta_k \text{ with } \Delta_i = \sqrt{\sum_{j=1}^{n} \Delta_{ij}^2} = \sqrt{\sum_{j=1}^{n} \left[\Gamma_j \left(\phi_{i,j} - \phi_{i-1,j}\right)\right]^2} \tag{3}$$

Since only the relative values of storey displacements (D_i) are of interest in the determination of the normalised modal scaling vector $\overline{D}$, which defines the shape, not the magnitude, of the load or load increment vector, the displacements obtained by Equation (3) are normalised so that the maximum displacement remains proportional to the load factor, as required within a load control framework:

$$\overline{D_i} = \frac{D_i}{\max D_i} \tag{4}$$

Once the normalised scaling vector and load factor have been determined, and knowing also the value of the initial nominal load vector, the loading vector U_t at a given analysis step t is obtained by adding to the load vector of the previous step, U_{t-1} (existing balanced loads), a newly derived load vector increment, computed as the product between the current load factor increment $\Delta\lambda_t$, the current modal scaling vector $\overline{D_t}$ and the nominal vector U_0, as mathematically translated into Equation (5) and graphically depicted in Figure 10.

$$U_t = U_{t-1} + \Delta\lambda_t \cdot \overline{D_t} \cdot U_0 \tag{5}$$

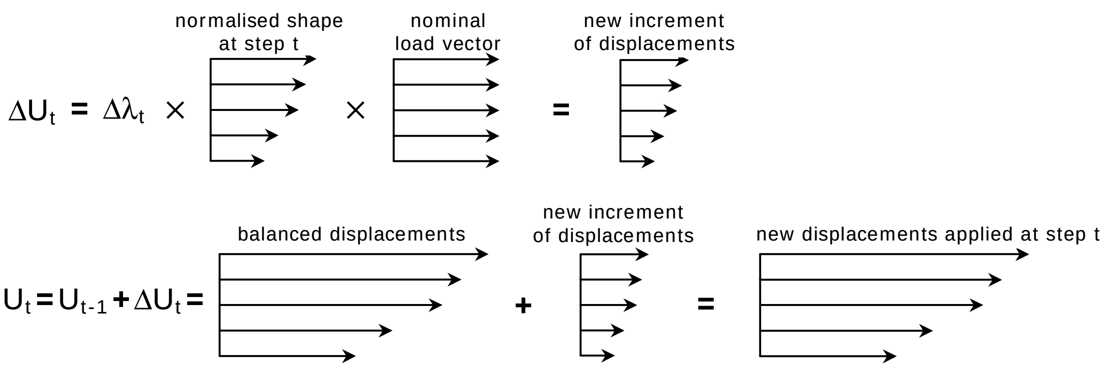


Figure 10: Updating of the loading displacement vector.

DAP – Case-studies and Modelling

As stated above, two clearly distinct building frames, both of which featuring an irregular type of dynamic response, have been considered in this work. The 12-storey five-bay reinforced concrete structure, design according to Eurocode 8 [4], displayed a highly irregular dynamic behaviour (e.g. Figure 3) when subjected to an accelerogram (Hollister station, Loma Prieta earthquake, USA, 1989) that presented a very high amplification in the short-period and thus lead to a response very much dominated by the 2nd and 3rd modes of vibration. Indeed, and as can be observed in Figure 11, these two higher modes ($0.15 < T_2, T_3 < 0.30$ secs) feature a spectral amplification, in acceleration, that is ten times higher than that corresponding to first mode of vibration ($T_1 > 1.4$ secs). Further details on this case-study can be found in [21].

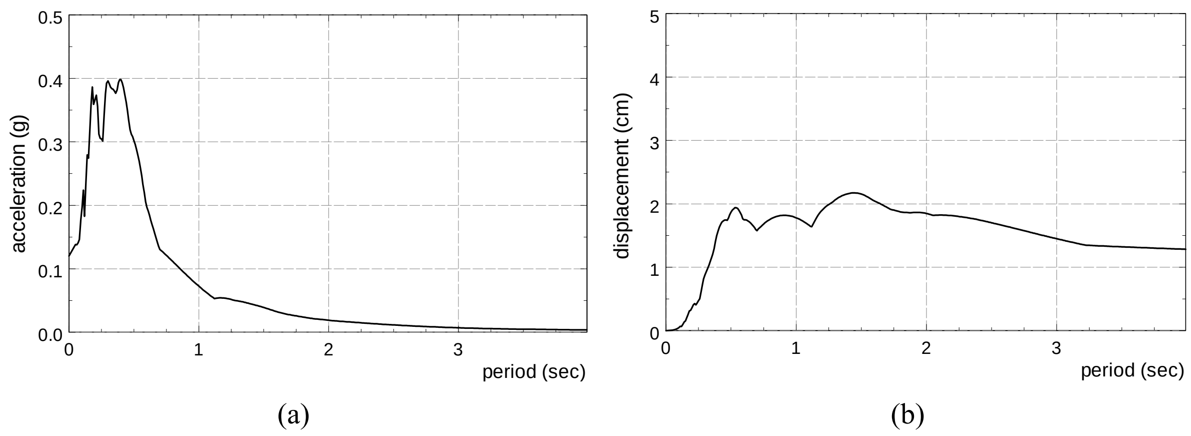


Figure 11: (a) Acceleration and (b) displacement response spectra of accelerogram employed in the analysis of 12-storey building.

The 4-storey three-bay building refers to a full-scale test specimen, built to represent typical design and construction practice in most South-European countries in the 1950's, and tested under pseudo-dynamic conditions [7] at the JRC in Ispra (Italy). The frame was designed for gravity loads only, without any consideration of ductility provisions or capacity design principles. Consequently, it exhibited a soft-storey type of deformation mechanism at the third storey level (e.g. Figure 3) caused mainly by the drastic stiffness/strength variation present at such location, as well as by inadequate lap-splicing and defective column shear capacity. The input motion consisted of artificial accelerograms aiming at being representative of European seismicity.

Finally, and for what concerns the Finite Elements Analysis package used in the present work, SeismoStruct [26], a fibre-element based program for seismic analysis of framed structures, which can be freely downloaded from the Internet, has been employed. The program is capable of predicting the large displacement behaviour and the collapse load of framed structural configurations under static or dynamic loading, accounting for geometric nonlinearities and material inelasticity. Its accuracy in predicting the seismic response of building and bridge structures has been demonstrated through comparisons with experimental results derived from pseudo-dynamic tests carried out on full or large-scale models (e.g. [7], [27]). Further, the package features also the readily availability of the displacement-based adaptive pushover algorithm employed in this study.

DAP – Results

One of the main advantages in using a displacement-based pushover procedure lays on the fact that storey forces or shears are no longer applied directly to the structure but rather come as a result of structural equilibrium to the applied displacement pattern, thus allowing for the reproduction of reversal of storey shear distributions, observed in dynamic analysis, even if a quadratic rule is employed to combine the contribution of the different modes. In effect, DAP drift profiles, despite carrying a permanently positive sign, do, in any case, feature changes of their respective gradient (i.e. the trend with which drift values change from one storey to the next), introduced by the contribution of higher modes. When such gradient variations imply a reduction of the drift of a given storey with respect to its adjacent floor levels, then the corresponding applied storey horizontal force must also be reduced, in some cases to the extent of sign inversion, as observed in Figure 12, below.

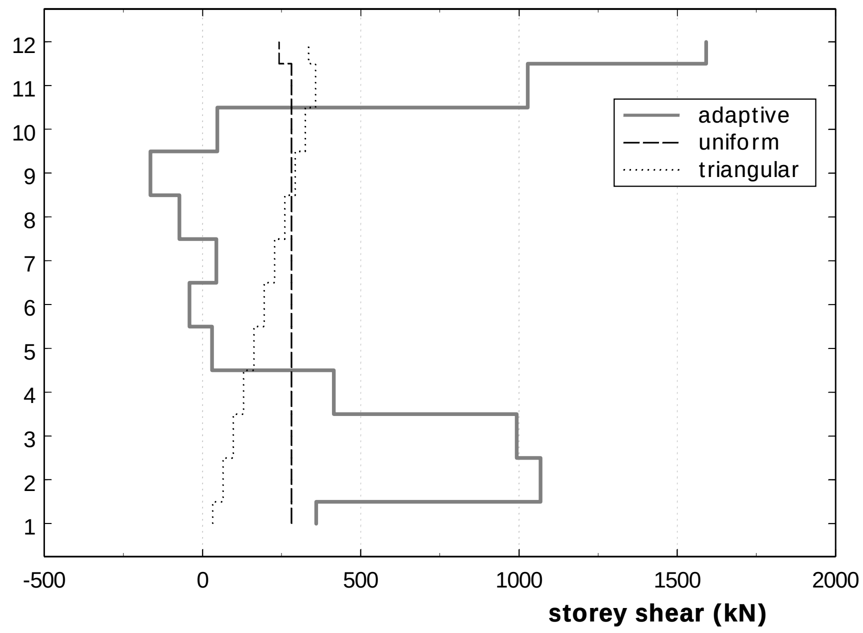
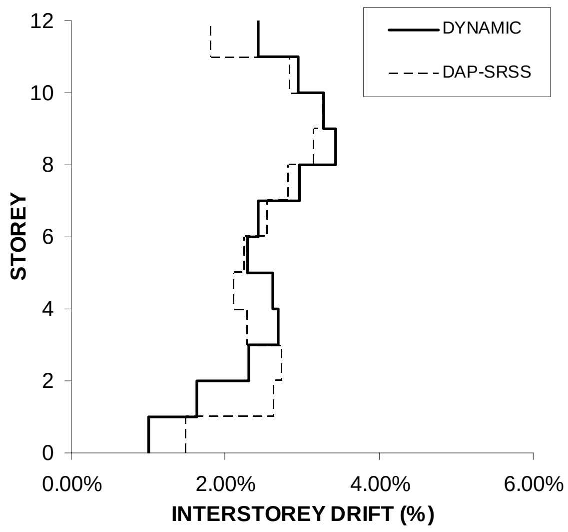


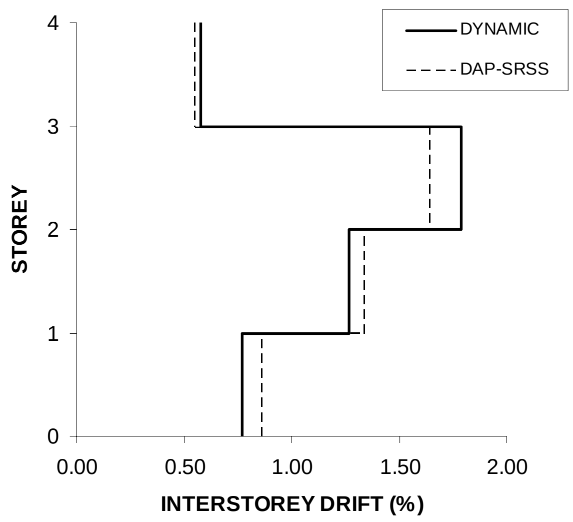
Figure 12: Storey shear distributions of a 12-storey building obtained with Displacement-based Adaptive Pushover as well as with standard non-adaptive pushovers.

In other words, given that in DAP, shear distributions are automatically derived to attain structural equilibrium with the imposed storey drifts, rather than being a result of the loads directly applied to the structure, the previously described limitations evidenced by force-based adaptive schemes that use quadratic modal combination rules can be overcome and, consequently, results as whole (i.e. deformation profiles and capacity curves) become more accurate. Further details and discussion on this issue can be found in [23].

In Figure 13, the interstorey drift profiles of the two case-studies being considered in this work, as obtained with the employment DAP analyses, are given. It is observed that the predictions now match much closer the dynamic response of these two structures, which effectively means that the response irregularities caused by the flexibility of the 12-storey structure, and subsequent amplification of higher modes, as well as the strength irregularity of the 4-storey prototype, have been fully and correctly captured by the proposed static analysis algorithm.



(a)



(b)

Figure 13: Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with Displacement-based Adaptive Pushover using SRSS combination.

In Figure 14, on the other hand, the capacity curves of the 12-storey building, as derived by both DAP and standard pushover curves are compared with the Incremental Dynamic Analysis envelope. The advantages of using an adaptive displacement-based pushover can be inferred also from this type of results.

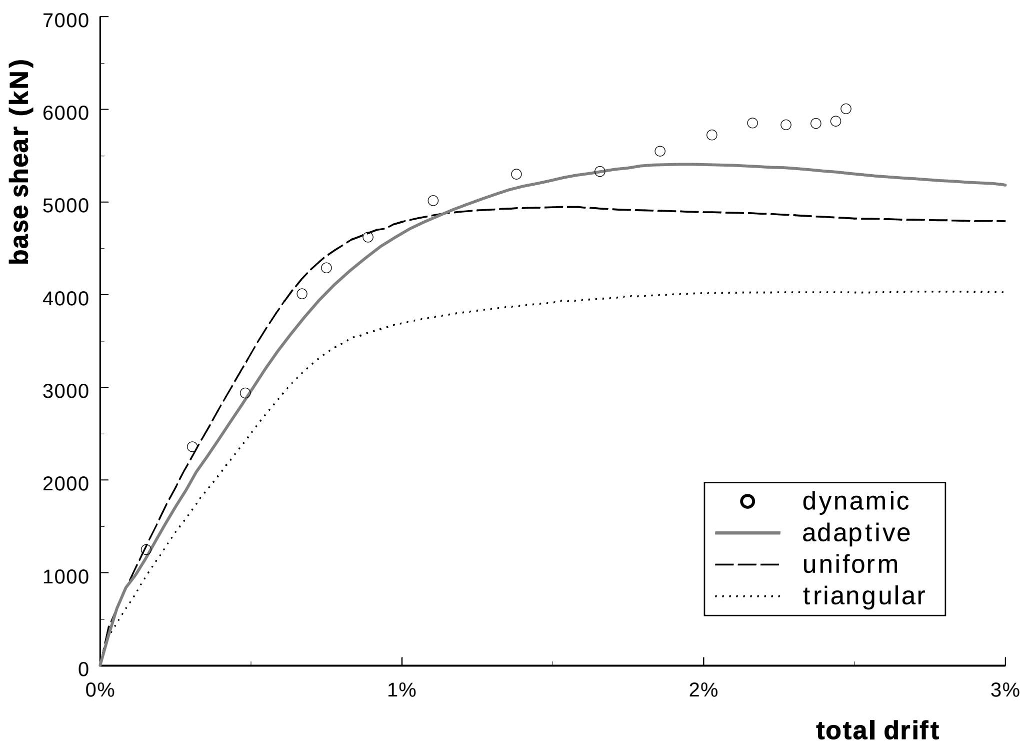


Figure 14: Capacity curves of a 12-storey building, obtained with DAP and standard pushovers, and compared against IDA envelopes.

DAP – Ease-of-use, Computational Effort and Numerical Stability

When compared with nonlinear time-history analysis, pushover methods are advantaged by their (i) higher user-friendliness, (ii) reduced running time and (iii) increased numerical stability. Therefore, it is important that the proposed displacement-based algorithm, capable of producing improved structural response predictions in comparison with existing non-adaptive pushover techniques, does also feature these three advantages over dynamic analysis.

From a usability point-of-view, the proposed displacement-based adaptive pushover algorithm effectively presents no additional effort and/or requirements with respect to its conventional non-adaptive counterparts. In effect, the only element of novelty, in terms of analysis input, is the introduction of the building's inertia mass, which, however, can readily be obtained directly from the vertical gravity loads, already included in any type of pushover analysis.

With regards to computational effort, in general, the amount of time necessary to complete an adaptive pushover analysis is typically double the time necessary for a conventional procedure, approximately. Obviously, the duration of such finite element runs will vary according to the computing capacity of the workstation being used, as well as with the characteristics of the model (mainly the number of elements and level of fibre discretisation of the sections). In any case, adaptive pushover proved to be up to ten times quicker than nonlinear dynamic analysis of a same model (keeping in mind that fibre-based finite element modelling has been adopted for the current work), hence the time-advantage of static methods versus their dynamic counterparts is not lost with the addition of the adaptive features.

As far as numerical stability is concerned, no particular problems are to be reported, noting that structures where pushed well into their post-peak inelastic response range (3% total drift). Finally, it is recalled that, as previously noted, DAP has been implemented in an Internet-downloadable Finite Elements Analysis program, hence the proposed displacement-based adaptive pushover scheme is readily available to practicing and research communities, in the form of a graphical-interfaced software package, adequate for general.

CONCLUDING REMARKS

A displacement-based adaptive pushover procedure (DAP), whereby a set of laterally applied displacements, rather than forces, is monotonically applied to the structure, has been briefly described and tested. In order to illustrate its potential advantages, with respect to traditional force-based pushover procedures, DAP has been employed in the assessment of the seismic capacity of two building frames featuring irregular dynamic response characteristics, caused by both the presence of higher mode effects as well as the existence of strength/stiffness irregularities.

The predictions of displacement-based adaptive pushover were compared to results derived by conventional pushover with different load distributions and rigorous dynamic time-history analysis, the latter being assumed as providing the "exact" response prediction to be used as benchmark. This demonstrative set of results indicates that, in comparison to force-based alternatives, DAP does manage to provide improved predictions, throughout the entire deformation range, of the dynamic response characteristics of irregular frames.

Hence, by adopting a displacement-based adaptive pushover, not only the attainment of more accurate results (deformation profiles and capacity curves) are warranted, but the entire structural assessment exercise becomes coherent with recent seismic design/assessment trends where the direct use of displacements, as opposed to forces, is preferred as a recognition of the conspicuous evidence that seismic structural damage is in fact induced by response deformations. In addition, and as far as the effort of the modeler/engineer is concerned, the additional modelling and computational effort requested to run such type of analysis is, with respect to conventional pushover procedures, negligible.

It is nonetheless noted that, although the proposed displacement-based pushover method does provide significantly improved predictions in comparison to existing force-based algorithms, rigorous reproduction of dynamic analysis response cannot still be achieved for a full range of case-studies, as extensive parametric studies [22, 25] seem to show. It is not clear if such limitations are inherent to the static nature of this numerical tool, or if they can be overcome through the introduction of alternative modal combination rules. Additional studies, currently underway, should clarify this matter.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the input of Dr M. Lopez and Dr C. Casarotti, both from the European School for Advanced Studies in Reduction of Seismic Risk (ROSE School, Pavia, Italy), who have contributed, through discussions, suggestions and analyses, to the current work. Further, the financial support of the European Commission, through the FP6 Integrated Project LESSLOSS (Risk Mitigation for Earthquakes and Landslides), is also gratefully acknowledged by the authors.

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