

## DEVELOPMENT AND VERIFICATION OF A DISPLACEMENT-BASED ADAPTIVE PUSHOVER PROCEDURE

S. ANTONIOU

*Department of Civil Engineering, Imperial College London,  
Imperial College Road, London SW7 2BU, UK*

R. PINHO

*European School for Advanced Studies in Reduction of Seismic Risk (ROSE School)  
Collegio Alessandro Volta, Via Ferrata 17, 27100 Pavia, Italy*

Received 25 November 2002

Revised 30 October 2003

Accepted 30 October 2003

In this paper, an innovative displacement-based adaptive pushover procedure, whereby a set of laterally applied displacements, rather than forces, is monotonically applied to the structure, is presented. The integrity of the analysis algorithm is verified through an extensive comparative study involving static and dynamic nonlinear analysis of 12 reinforced concrete buildings subjected to four diverse acceleration records. It is shown that the new approach manages to provide much improved response predictions, throughout the entire deformation range, in comparison to those obtained by force-based methods. In addition, the proposed algorithm proved 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. This novel adaptive pushover method is therefore shown to constitute an appealing displacement-based tool for structural assessment, fully in line with the recently introduced deformation- and performance-oriented trends in the field of earthquake engineering.

*Keywords:* Displacement-based adaptive pushover; interstorey drifts; DAP.

### 1. Introduction

The fact that earthquake input has been modelled as forces rather than displacements can only be explained by historical reasons, related to the development of contemporary engineering methods in countries of low seismic hazard, like England and Germany, where the most significant actions are vertical gravity loads. Had modern engineering made its initial step in earthquake-prone regions like New Zealand, California or Southern Europe, today's code provisions would probably be based on deformations. Such belief is backed up by the present drive for development and code implementation of displacement- or, more generally, deformation-based design and assessment methods, triggered by the work of a number of researchers in the past decade [e.g. Moehle, 1992; Calvi and Pavese, 1995; Kowalsky *et al.*, 1995; Priestley, 1997].

Taking the above into account, it would therefore seem that applying displacement loading, rather than force actions, in pushover procedures would be the most appropriate and theoretically robust option for nonlinear static analysis of structures subjected to earthquake action. However, conventional (non-adaptive) displacement-based pushover analysis suffers from significant inherent shortcomings that prevent its use as a reliable structural evaluation tool. Indeed, due to the unvarying nature of the applied displacement loading vector, such method 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 on the development and verification of such an innovative displacement-based adaptive pushover method (DAP).

In order to verify the integrity of the proposed analysis algorithm, a series of DAP and conventional pushover analyses is carried out and compared with the predictions of inelastic dynamic analysis, employing a large set of structural models and ground motions of diverse characteristics. It is shown that, in all applications, the new approach yields response predictions that are superior, or at worse equivalent, to those obtained by its force-based counterparts. In addition, the innovative algorithm proved 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.

## **2. Non-Adaptive Displacement-Based Pushover**

As mentioned above, the modelling of earthquake actions as lateral displacements rather than forces constitutes a more natural and rational approach. Hence, there seems to exist a solid rationale for preferring the application of displacement rather than force patterns in pushover analysis. However, although conceptually sounder, serious practical problems arise with conventional deformation-based pushover of buildings, mainly due to the fact that the relative displacement between consecutive floor levels is fixed, thus concealing significant structural characteristics and leading to misleading results.

Indeed, it is unrealistic to expect the ratio between displacements at every two successive storeys to remain constant throughout the entire structural deformation range. This is because deformations generally tend to be more evenly distributed in the elastic range, whereas in the post-yield phase they concentrate on zones where

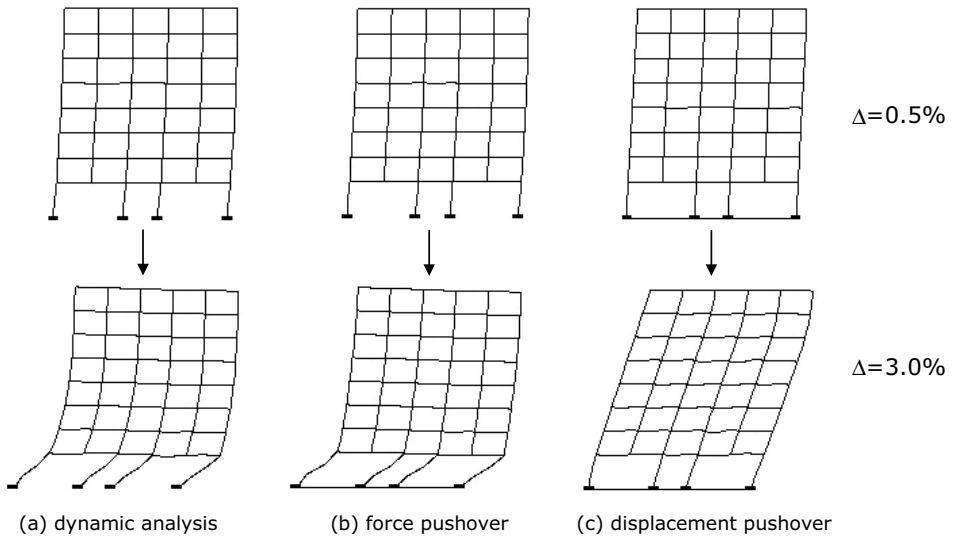


Fig. 1. Deformed shapes of an 8-storey building; (a) dynamic analysis; (b) conventional force-based pushover (triangular distribution); (c) conventional displacement-based pushover (triangular distribution).

plastic hinges have formed. Such behaviour, and the resulting unsuitability of fixing the relative storey displacements in pushover analysis, is illustrated in Fig. 1, where the deformed shapes of an 8-storey irregular building obtained through dynamic and conventional (displacement- and force-based) pushover analyses are depicted. The shapes are shown for two different deformation levels; 0.5% and 3.0% global drift.

As observed in Fig. 1, the dynamic floor displacements in the pre-yield range (0.5% drift) do tend to be evenly distributed. In the inelastic range (3% drift), however, they are considerably larger at the location of plastic hinging (at the ground soft storey for this particular example). This implies that the displacement profiles for different deformation levels are different and it is thus unreasonable to expect that displacement-based pushover analysis with fixed patterns can provide an accurate picture of the structural behaviour for the entire range of deformations.

The above considered, it is thus not surprising that capacity curves derived with conventional displacement-based pushover can be widely different from the actual dynamic response envelopes of the structure, as depicted in Fig. 2, below. Indeed, the fixed triangular displacement forcing vector applied to the 8-storey building considered in this example, constrains the structure to follow a pre-defined collapse mechanism that does not involve a soft-storey failure at the ground floor, as expected in this case. Hence, the capacity curve derived from such conventional displacement-based pushover is unable to predict the actual base shear and deformation capacities mobilised by the same structure when subjected to earthquake action, strongly underestimating the former and over-predicting the latter.

It is thus evident that if displacement loading is to be employed in pushover runs, a way of realistically updating the deformation patterns, so as to reflect the

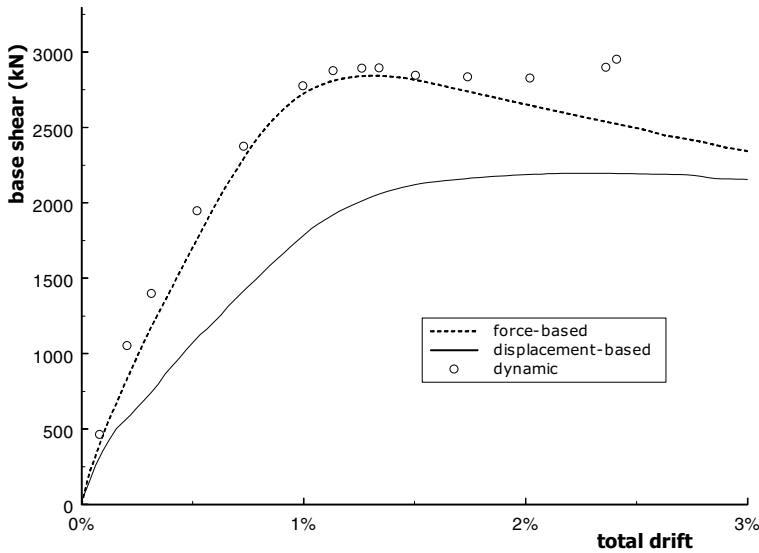


Fig. 2. Dynamic envelope and conventional pushover curves for the building considered in Fig. 1.

actual stiffness characteristics of the structure at each step of the analysis, must be introduced. The adaptive pushover algorithm described in the companion paper [Antoniou and Pinho, 2004], initially developed for force-based applications, has therefore been adapted here to the case of pushover under a displacement loading vector. As shown in subsequent sections of this presentation, the resulting novel methodology does manage to overcome the limitations of non-adaptive displacement-based pushover analysis.

### 3. The Displacement-Based Adaptive Pushover Algorithm (DAP)

The displacement-based adaptive pushover algorithm adopted and developed within the current work has been implemented in SeismoStruct [SeismoSoft, 2004], a fibre-modelling Finite Element program for seismic analysis of framed structures, which can be freely downloaded from the Internet. Full details on this computer package can be found in its accompanying manual.

The implementation of the proposed algorithm can be structured in four main stages; (i) definition of nominal load vector and inertia mass, (ii) computation of load factor, (iii) calculation of normalised scaling vector and (iv) update of 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.

Steps (i) and (ii) above are identical to those described in the companion paper [Antoniou and Pinho, 2004], with the only difference consisting on the fact that the load vector now consists of displacements ( $U$ ), rather than forces ( $P$ ). In general

terms, the former is obtained, at each step of the analysis, through Eq. (1), where  $\lambda$  represents the load factor, determined by means of a *load control* algorithm (Sec. 3.2 of companion paper) and  $U_0$  is the nominal load vector (Sec. 3.1 of companion paper):

$$U = \lambda \cdot U_0. \quad (1)$$

It is noted that in DAP, applied loads and response deformations can be considered as effectively coincident, since both the former as well as the latter consist of displacements. Hence, the employment of the slightly more elaborated response control algorithm, adopted in the companion paper for the FAP method, is not required here, in view of the fact that both load and response control types lead to the attainment of equal results. For this reason, the simpler load control algorithm was implemented instead.

### 3.1. Calculation of normalised scaling vector

The normalised modal scaling vector  $\bar{D}$ , used to determine the shape of the load vector (or load increment vector) at every step, is computed at the start of every load increment. In order for such scaling vector to reflect the actual stiffness state of the structure, as computed at the end of the previous load increment, an eigenvalue analysis is firstly carried out. To this end, the Lanczos algorithm [Hughes, 1987] is employed to determine the modal shapes and participations factors of any given pre-defined number of modes.

In the proposed method, modal results can be combined together using either the SRSS or CQC combination rules, described in the companion paper. However, for the purpose of the current work, and given that observed modes of vibration at each analysis step were always sufficiently apart, the SRSS combination rule was employed throughout. This choice is reflected in subsequent equations, where the procedure for the computation of the scaling displacement vector  $D$ , through displacement- or drift-based approaches, is described.

*Displacement-based scaling* refers to the case whereby storey displacement patterns  $D_i$  are obtained directly from the eigenvalue vectors, as described in Eq. (2a), where  $i$  is the storey number and  $j$  is the mode number,  $\Gamma_j$  is the modal participation factor for the  $j$ th mode,  $\phi_{ij}$  is the mass normalised mode shape value for the  $i$ th storey and the  $j$ th mode, and  $n$  stands for the total number of modes. This first approach is analogous to the force-based adaptive procedure presented in the companion paper, making use of the maximum storey displacements calculated directly by modal analysis to determine the scaling displacement vector:

$$D_i = \sqrt{\sum_{j=1}^n D_{ij}^2} = \sqrt{\sum_{j=1}^n (\Gamma_j \phi_{ij})^2}. \quad (2a)$$

The maximum displacement of a particular floor level, however, being essentially the relative displacement between that floor and the ground, provides insufficient insight into the actual level of damage incurred by buildings subjected 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. Hence, an alternative scaling scheme, 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, has also been developed.

In such *interstorey drift-based scaling* technique, the eigenvalue vectors are thus employed to determine the interstorey drifts for each mode  $\Delta_{ij}$ , as shown in Eq. (2b), whilst the displacement pattern  $D_i$  at the  $i$ th storey is obtained through the summation of the modal-combined interstorey drifts of the storeys below that level, i.e. drifts  $\Delta_1$  to  $\Delta_i$ :

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

The accuracy gains stemming from the use of interstorey drift-based scaling, in comparison to its displacement-based scaling counterpart, are illustrated in Fig. 3, where the results of these two scaling alternatives are compared to dynamic analysis envelopes obtained for a representative model (see Sec. 4). Whilst the capacity curves obtained with both methods are very similar, with relatively minor advantages being observed for the case of interstorey drift-based DAP, the prediction of drift profiles results improved with the employment of interstorey drift-based scaling. For this reason, interstorey drift-based scaling has been adopted as the standard DAP variant, hence, in the remaining of the paper, every mention to displacement-based adaptive pushover refers to its drift-based scaling version.

It is nonetheless noted that, although the summation of modal interstorey drifts constitutes an improvement over direct combination of displacements, it is still approximate, since it assumes that all drift maxima at different stories occur at the same time, which is of course not realistic. Furthermore, and as discussed already in the companion paper, the use of SRSS or CQC rules to combine modal results will inevitably lead to not entirely correct load vector shapes, since the possibility of sign change in storey displacements or interstorey drifts from different modes is not catered for. The assessment of the effects that these inconsistencies might have on obtained results could not, however, be carried out in the current presentation, since the possible alternative of carrying out weighted vectorial addition of the contribution of each mode calls for additional in-depth studies that were noticeably beyond the scope of the present endeavour. Hence, the traditional SRSS/CQC modal combination rules have been employed instead, leading to nonetheless much improved results, as shown in Sec. 4 below.

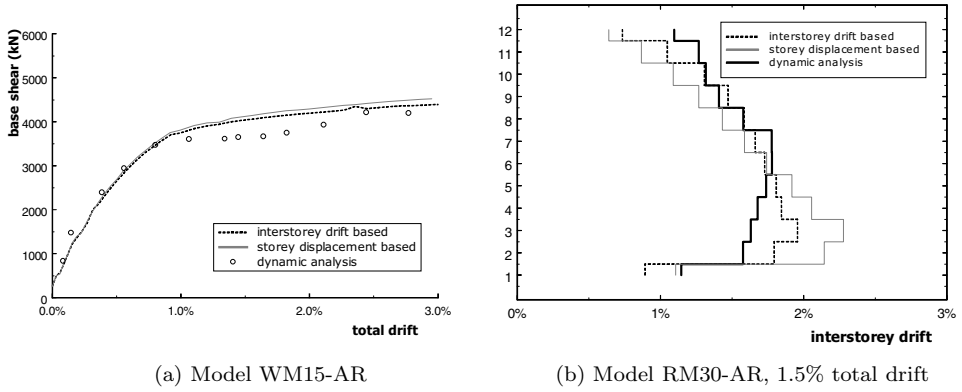


Fig. 3. Representative DAP results obtained with drift-based and displacement-based adaptive pushovers.

The definitive implementation of the proposed DAP algorithm featured the employment of Eq. (3) rather than Eq. (2b), given above. In effect, the former includes an additional parameter  $S_{d,j}$  that represents the displacement response spectrum ordinate corresponding to the period of vibration of the  $j$ th mode, hereafter referred to as *spectral amplification*. In other words, the modal interstorey drifts are weighted by the  $S_d$  value at the instantaneous period of that mode, so as to take into account the effects that the frequency content of a particular input time-history or spectrum have in the response of the structure being analysed.

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

The importance of including spectral amplification in the computation of the scaling displacement vector is demonstrated by the results shown in Fig. 4, where capacity curves and drift profiles obtained with and without spectral amplification are compared to the dynamic analysis results of some representative models, described in Sec. 4. It is observed that the predictions of both capacity curves and drift profiles are significantly bettered when spectral amplification is considered, a feature confirmed for all case studies. This considerable underperformance of the non-spectral variant of the method is caused by the inappropriate “always-additive” inclusion of higher modes contribution through a non-weighted (i.e. without  $S_d$ ) SRSS combination rule, as clearly depicted in Fig. 4(b). Consequently, and as mentioned above, within the current work, all DAP analyses feature the inclusion of spectral amplification.

As noted already in the companion paper [Antoniou and Pinho, 2004], where the FAP algorithm is described, multiple response spectra, derived for varying values of equivalent viscous damping, should ideally be employed so as to reflect the actual energy dissipation characteristics of the structure at each deformation level (i.e. at

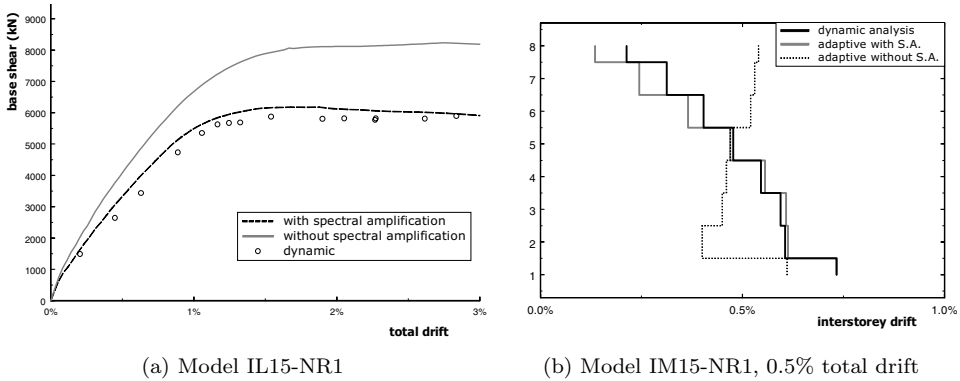


Fig. 4. Representative DAP results obtained with and without spectral amplification.

each analysis step). The implementation of such refinement, however, was beyond the scope of the current work, for which reason a single constant response spectrum derived for an equivalent viscous damping value of 5% was used throughout the entirety of each analysis. Future work will target the assessment of the effects that such apparent limitation has on attained results.

Since only the relative values of storey displacements ( $D_i$ ) are of interest in the determination of the normalised modal scaling vector  $\bar{D}$ , which defines the shape, not the magnitude, of the load or load increment vector (see Subsec. 3.2), the displacements obtained by Eq. (3) are normalised so that the maximum displacement remains proportional to the load factor, as required within a load control framework:

$$\bar{D}_i = \frac{D_i}{\max D_i}. \quad (4)$$

Similar to the FAP algorithm, and for the reasons pointed out in the companion paper, when the structural response reaches its post-peak range, the load vector shape is no longer changed (only its magnitude is updated), effectively meaning that a conventional non-adaptive pushover analysis is employed thereafter. Finally, and although an update frequency of the load vector shape lower than the number of analysis steps could have been easily adopted, for reduced computational effort, within the framework of the current parametric study the load vector shape was updated at every analysis step, with up to ten modes of vibration being considered in its computation. In this manner, increased accuracy and analysis stability were ensured.

### 3.2. Update of loading displacement vector

Once the normalised scaling vector  $\bar{D}_t$  and load factor  $\lambda_t$  or load factor increment  $\Delta\lambda_t$  have been determined, and knowing also the value of the initial nominal load vector  $U_0$ , the loading displacement vector  $U_t$  at a given analysis step  $t$  can be updated using one of two alternatives introduced in the companion paper; total or



incremental updating, herein translated into Eqs. (5a) and (5b), respectively:

$$U_t = \lambda_t \cdot \overline{D}_t \cdot U_0, \quad (5a)$$

$$U_t = U_{t-1} + \Delta \lambda_t \cdot \overline{D}_t \cdot U_0. \quad (5b)$$

However, and as already observed for the case of FAP, total updating featured a conspicuous lack of numerical stability that rendered unfeasible its application to the current parametric study. Furthermore, in those few cases where total-updating analyses could be completed, the results obtained proved to be highly inaccurate, as shown in Fig. 5, where the static and dynamic responses for two illustrative cases are depicted.

The inadequacy of total updating is further asserted by the plots of Fig. 6, where the interstorey drift profiles corresponding to the pushover analyses indicated in Fig. 5(a), before and after the formation of the yielding mechanism, are shown. It is clear that the onset of damage at a particular location leads to a rearrangement of the applied lateral displacements that over-estimates the deformations in that area, thus inducing flawed predictions and, very often, instabilities. It is a pattern similar to the exaggerated concentration of loads in locations of damage observed for the FAP method, discussed in the companion paper.

The above renders clear that total updating cannot be used with displacement-based adaptive pushover. On the contrary, incremental updating, due to the gradual modification of the load profiles, does not present stability problems, providing also more accurate estimates of the dynamic response characteristics for the examined building structures. For this reason, Eq. (5b), which effectively replaces the generalist and merely indicative Eq. (1), previously introduced, was adopted throughout the current parametric study.

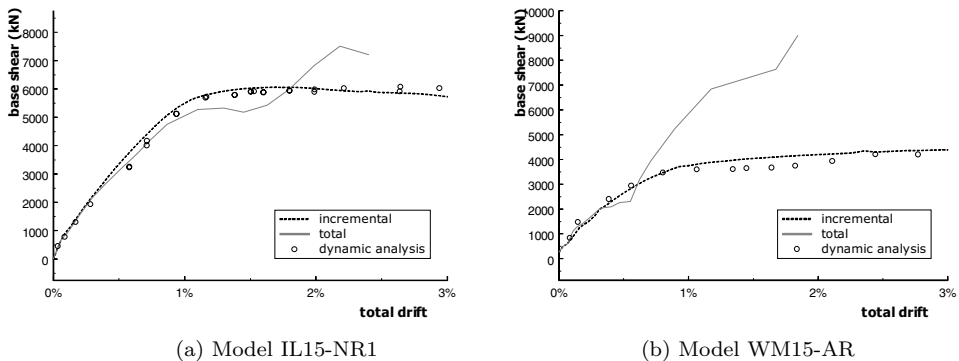


Fig. 5. Displacement-based adaptive pushover curves with total and incremental updating.

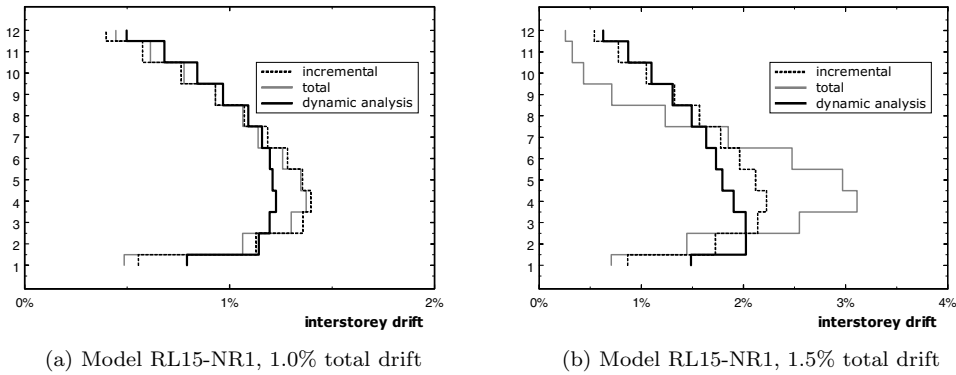


Fig. 6. Interstorey drift profiles obtained with total and incremental updating.

## 4. Parametric Study

### 4.1. Introduction

In order to assess the accurateness of the proposed DAP method, an extensive comparative study has been carried out, involving static and dynamic nonlinear analysis of twelve reinforced concrete buildings (4 regular frames, 4 irregular frames and 4 wall-frame buildings) subjected to four diverse acceleration records (1 artificial and 3 natural). The displacement response spectra of the latter, used in the compu-

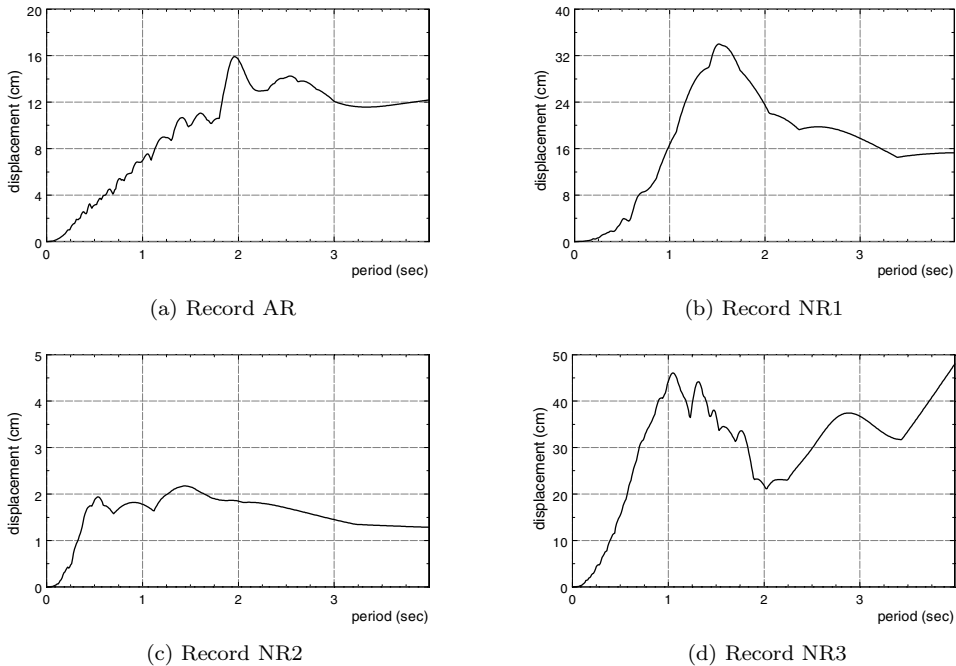


Fig. 7. Elastic displacement spectra of the records considered (5% equivalent viscous damping).

tation of the normalised scaling vector, are illustrated in Fig. 7. It is noted that the very same structural models and input motion employed in the force-based pushover study described in the companion paper [Antoniou and Pinho, 2004] have been utilised. Therefore, and for the sake of succinctness, detailed description of such models is not included here, for which reason the reader should instead refer to the companion publication whenever such information is required or useful.

For each one of the 48 case studies, a displacement adaptive pushover, in its drift-based variant with incremental updating and spectral amplification, was compared to the conventional uniform and triangular force-based pushovers suggested in the FEMA guidelines [ATC, 1997] and to the envelopes derived through Incremental Dynamic Analysis (20 time-history runs per case study). In addition to the capacity curves, the interstorey drift and storey shear profiles at four different deformation levels (0.5%, 1.0%, 1.5% and 2.5% total drift) were also produced, so as to assess the accuracy of the method in reproducing local response characteristics. All the analyses were carried out up to the point of 3% global drift, employing the previously introduced FE package, SeismoStruct, described in further detail in the companion paper, where a discussion of the modelling assumptions adopted in the present work is also made.

Finally, it is noted that all pushover results are compared with IDA output obtained for each single accelerogram, as opposed to the statistical average of all dynamic cases, ensuring a very demanding and precise assessment of the static procedures, since structural response peculiarities introduced by individual input motions are not smoothed out through results averaging. Within this non-statistical verification framework, and in order to facilitate interpretation of the most important observations and exemplification of the significant conclusions, only representative plots are given hereafter. Readers interested in the full collection of results that have been post-processed are referred to the work of Antoniou [2002].

#### 4.2. Capacity curves

In Fig. 8, a series of top displacement versus base shear plots, comparatively illustrating static and dynamic results obtained for models with different structural characteristics subjected to equally diverse earthquake records, is given. It is also noted that, for the reasons provided in the companion paper, the dynamic analysis envelopes consist of the locus of maximum total drift versus corresponding base shear (i.e. peak base shear within a time-window  $\pm 0.5$  seconds of the instant of maximum drift occurrence).

It is observed that, similarly to its force-based counterpart, displacement-based adaptive pushover provides a closer fit to the dynamic analyses envelopes than the two conventional pushovers considered in this study. In cases where the input motion presented “limited complexities”, for which, in general, the force-based techniques performed well, DAP predictions proved to be very similar to the FAP ones, usually lying between the uniform and the triangular curves in both pre- and post-yield

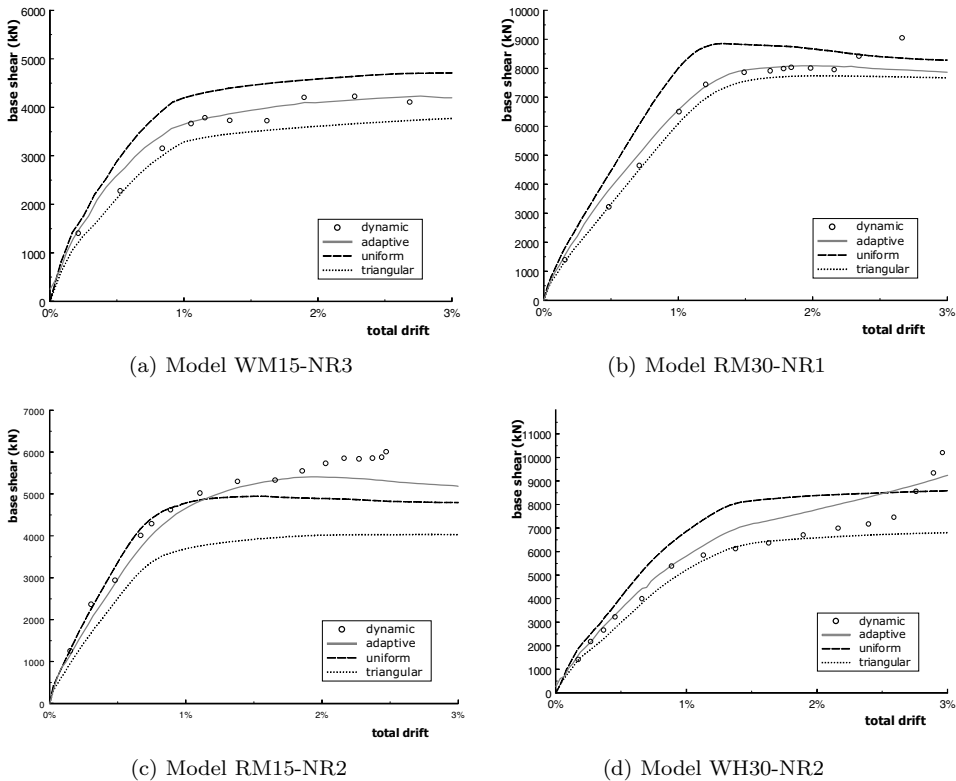


Fig. 8. Displacement-based adaptive and force-based conventional pushover curves.

response ranges. Typical examples of such “regular” type of response are the plots of Figs. 8(a) and 8(b). For these cases, DAP provided satisfactory results, however without impressive enhancements of the predictions with respect to the force-based adaptive method [see Antoniou and Pinho, 2004].

The displacement-based variant, however, exhibited its true potential in those cases where changes in the modal characteristics of the structure (induced by damage accumulation), resulting in the activation of vibration modes substantially different from those governing the elastic response, introduced dynamic response intricacies that force-based static methods could not reproduce. These peculiar, and not-so-frequent, response scenarios are depicted in Figs. 8(c) and 8(d), where it is observed that DAP manages to reproduce odd dynamic envelope trends where response points that initially lie between the two conventional pushovers then ascend over the uniform distribution. Such response prediction capacity was not observed with any force-based pushover, adaptive or not (see companion paper).

### 4.3. Interstorey drift profiles

In Fig. 9, the interstorey drift profiles obtained with DAP for model RM15-NR2, are compared to the estimates of conventional force-based pushover (uniform and

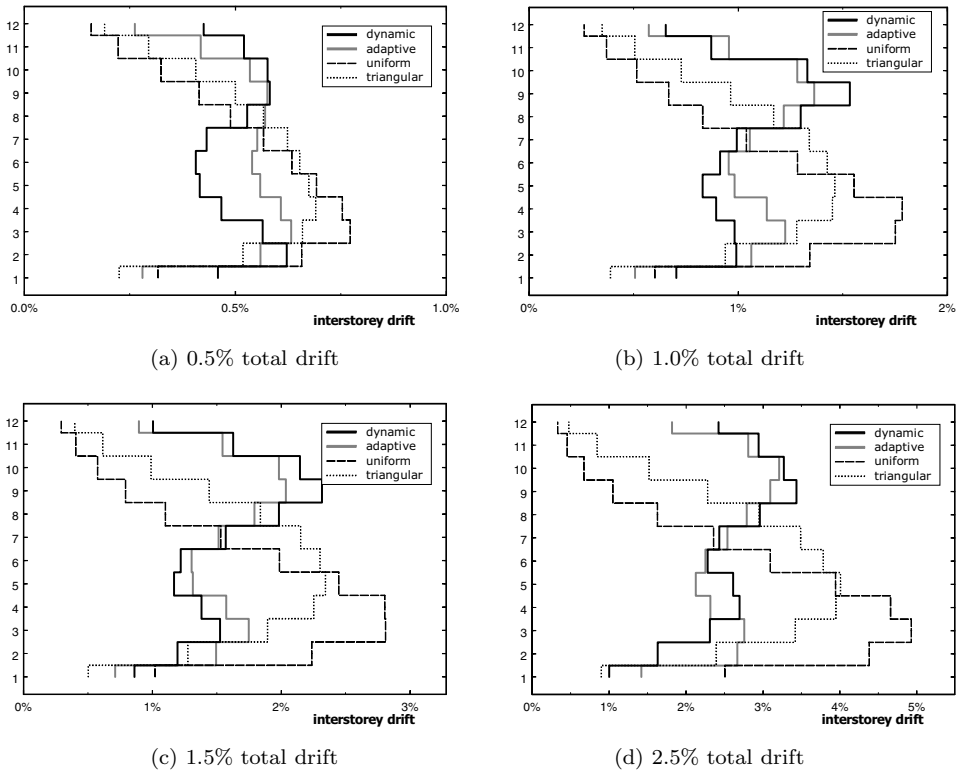


Fig. 9. Model RM15-NR2. Interstorey drift profiles at different deformation levels.

triangular distributions) and the dynamic analysis envelopes. The selected record was deliberately chosen as that for which all the force-based variants, adaptive or fixed, failed to provide acceptable response predictions for the entire set of analysed buildings, even within the pre-yield range. Due to the effects of higher modes, highly amplified by record NR2, the dynamic drifts tend to increase from the structure's mid-height upwards, a feature that all force-based static techniques struggled to reproduce. On the contrary, displacement-based adaptive pushover did manage to provide much improved approximations of such highly irregular dynamic deformation profile envelopes, for the entire range of deformations. In effect, even though attainment of fully accurate predictions was not observed, the DAP algorithm was consistently capable of reproducing the correct “trend” of the IDA drift envelopes, a feature seemingly beyond the capabilities of the force-based pushovers considered in the companion paper.

In addition, displacement-based pushover performed well also with other strong motions. A typical case is illustrated in Fig. 10, where the artificial record is employed. In this scenario, the dynamic drift envelopes no longer present the peculiar shapes of those shown in Fig. 9 above, for which reason the prediction improvements given by DAP are not as noticeable and significant, albeit still present. Overall, and considering the entire collection of results obtained [Antoniou, 2002], herein

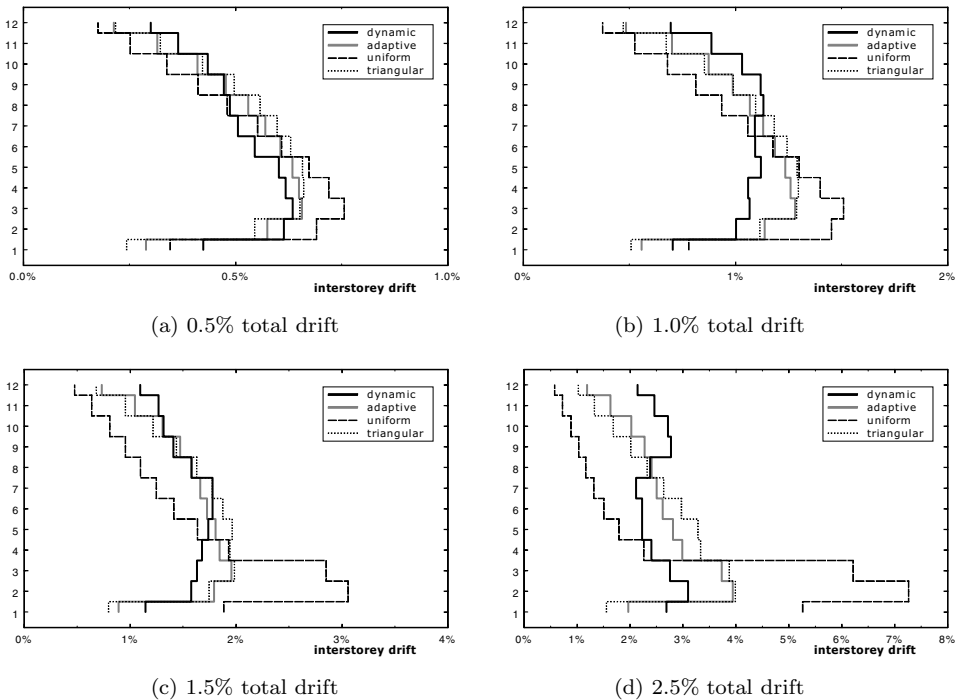


Fig. 10. Model RM30-AR. Interstorey drift profiles at different deformation levels.

represented by two typical examples, it can be stated that the displacement-based adaptive pushover algorithm exhibited an ability to better predict, in comparison to its force-based counterpart, the dynamic interstorey drifts for all types of structural configurations and ground motions.

#### 4.4. Storey shear profiles

In Fig. 11, the storey shear profiles obtained for case study RM15-NR2 are given. It is observed that the prediction improvements introduced by the use of DAP are not as clear and evident as those observed for the other two response parameters of the same model; drift profile (Fig. 9) and capacity curve (Fig. 8(c)). In effect, in the case of dynamic shear profile estimation, all static methods considered in this study, provide, for this example, poor absolute value estimates. However, it is nonetheless clear that the shear profile computed by DAP is, amongst those predicted by static methods, the only that somehow manages to follow the trends of the dynamic envelopes at all deformation levels.

Analysis of the storey shear distribution can also be used to gain a deeper insight into the reasons behind the observed superiority of DAP in predicting the capacity curves and drift profiles of all case studies considered in this work. From the cumulative shear profiles given in Fig. 11, the lateral forces applied at each

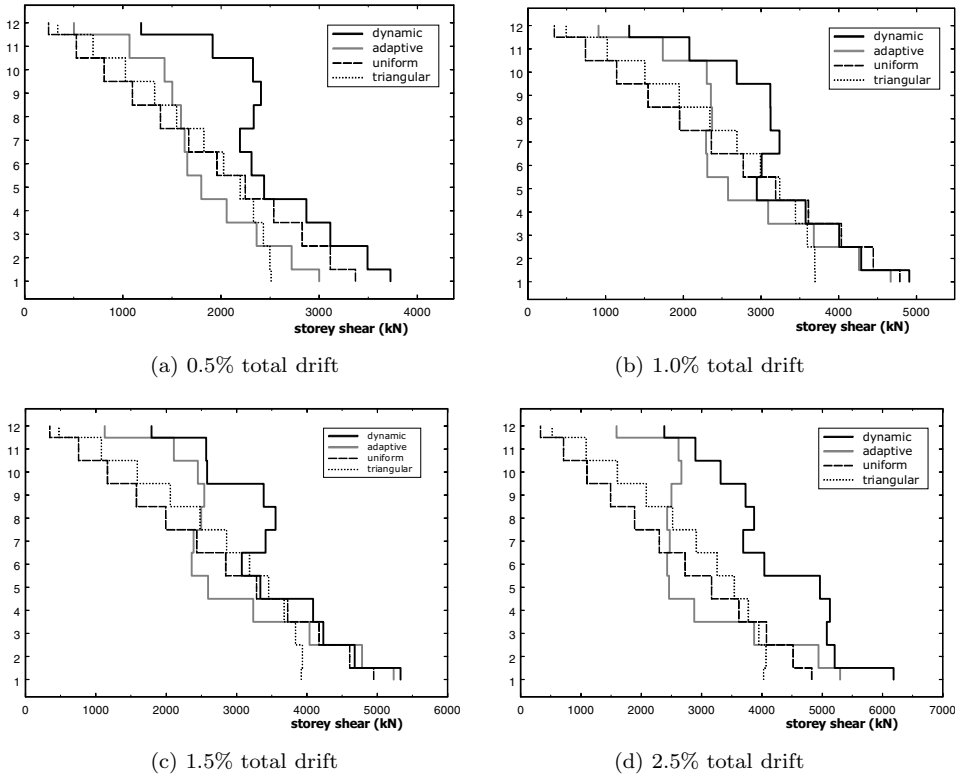


Fig. 11. Model RM15-NR2. Storey shear profiles at different deformation levels.

storey during the pushover analyses can be extracted (see Fig. 12). For the case of DAP, the results are highly irregular for the entire range of drifts, as opposed to the conventional pushover solutions which follow the expected triangular and uniform distribution. More importantly, it is observed in Fig. 12(c) that the DAP storey shear distribution at 1.5% drift is such that an inversion of the lateral forces at storeys 5 to 9 takes place, a response feature that is out-of-reach of any of the force-based static methods, adaptive or not, employed in the companion paper. Indeed, and as discussed by Antoniou and Pinho [2004], it is this impossibility of introducing inversion of the applied storey shear forces in force-based adaptive pushover schemes, stemming from the “always-additive” SRSS combination rule employed in the computation of the normalised scaling vector, that prevents such procedures from reproducing the irregular displacement and shear profile shapes observed in some dynamic analysis.

In the present implementation of the DAP algorithm, SRSS is also used to combine the contributions of each mode, thus implying permanently positive storey drift profiles. As noted in Sec. 3.1, and as far as the capability to reproduce dynamic response characteristics is concerned, this constitutes a limitation of the method since

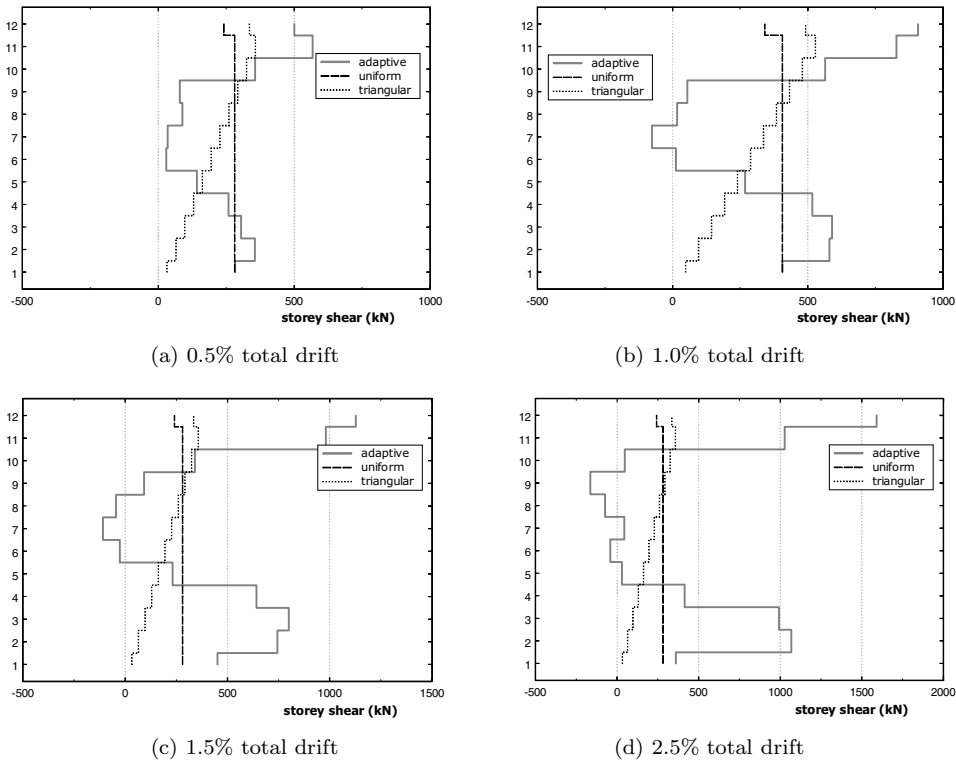


Fig. 12. Model RM15-NR2. Lateral force distributions at different deformation levels.

there will be cases, in dynamic analysis, where inversion of the sign of storey drifts does occur. However, 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 (see Fig. 9). When such gradient variations imply a reduction of the drift of a given storey with respect to its two 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 Fig. 12.

In other words, given that in DAP, shear distributions are automatically derived by the program's solver to attain structural equilibrium at the imposed storey drifts, rather than being a result of the loads directly applied to the structure, the limitations evidenced by force-based schemes in predicting the shear profiles are overcome and, consequently, results as whole (i.e. deformation profiles and capacity curves) become more accurate. This sets in evidence that even for shear force estimation it is more effective to impose a set of storey displacements, computed from modal analysis, on the structure and then estimate the lateral forces that correspond to them, than it is to adopt the inverse approach.



Apart from illustrating the advantages of the proposed DAP procedure, Fig. 12 highlights also the inadequacy of force-based techniques to describe complex dynamic behaviours. Indeed, the two fixed force distributions are obviously incorrect (their poor comparison with dynamic analysis envelopes can be inferred from Fig. 11), thus resulting in unrealistic predictions of storey drift and shear profiles.

## 5. 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 adaptive and non-adaptive pushover techniques, does also feature these three advantages over dynamic analysis. After all, a static procedure that is hard or time-consuming to use, would undermine its basic purpose, which is that of providing engineers with an accurate and simple tool for everyday practice.

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 usually be obtained directly from the vertical gravity loads, already included in any type of pushover analysis. Users should also take notice that, when defining the nominal displacement load vector at the start of the analysis, nominal nodal displacements must be introduced in the correct sequence of floors (i.e. 1st floor load being entered first, followed by the displacement nominal load at level 2, and so on), so that Eq. (3) can be used.

With regards to computational effort, and in general terms, the computation time required to complete an adaptive pushover analysis was approximately double the time necessary for a conventional procedure. 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 reduced but not lost with the addition of the adaptive features.

As far as numerical stability is concerned, and as stated in Sec. 3.2, the use of an incremental load vector updating scheme warranted full numerical stability for all cases considered, noting that structures were pushed well into their post-peak inelastic response range (3% total drift), as observed from the capacity curves included in the body of the document.

Finally, it is recalled that, as previously noted, DAP has been implemented in an Internet-downloadable Finite Element program, hence the proposed displacement-based adaptive pushover scheme is readily available in a graphically-interfaced software package, adequate for general use.

## 6. Conclusions

An innovative displacement-based adaptive pushover procedure (DAP), whereby a set of laterally applied displacements, rather than forces, is monotonically applied to the structure, has been proposed. The novel algorithm, being fully displacement-based, fits well within the current drive for the development and implementation of conceptually sounder nonlinear analysis tools for use within a performance and displacement-based design/assessment framework.

As far as the inner workings of the numerical algorithm is concerned, the main advantage of DAP resides on the fact that lateral deformations are directly determined through modal analysis that takes into consideration the stiffness state of the structure at each step, whilst storey shear force distributions result from the imposition of structural equilibrium at each analysis step. In this manner, response prediction limitations observed with force-based pushover methods are overcome.

In order to appraise the effectiveness and accuracy of the proposed scheme, an extensive parametric study was carried out and the predictions of displacement-based adaptive pushover were compared to results derived by rigorous dynamic time-history analyses as well as conventional pushovers with different load distributions. It was shown that, in comparison to force-based alternatives, DAP manages to provide greatly improved predictions, throughout the entire deformation range, of the dynamic response characteristics of different types of reinforced concrete frames subjected to equally distinct earthquake records.

Considering that its usage is as simple as any other pushover method, and that it exhibited a stable behaviour for all the analysed cases, it can be asserted that DAP constitutes a ready-to-use nonlinear static analysis method, standing as an appealing alternative to existing force-based pushover schemes. Hence, its employment in those cases where the use of rigorous time-history analysis is not justified or feasible, is recommended.

In closing, it is noted that, although the proposed displacement-based pushover method does provide significantly improved predictions in comparison to existing force-based algorithms, exact reproduction of dynamic analysis response could not be achieved. 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 (i) varying-damping response spectra and (ii) weighted vectorial addition combination rules in the computation of the modal normalised scaling vector. Additional studies, currently underway, should clarify this matter.

## Acknowledgements

The first author would like to acknowledge the financial support provided by the European Commission, through a Marie Curie Fellowship at the ROSE School (Pavia, Italy). The authors are also grateful to Professor Nigel Priestley for his insightful comments and suggestions.

## References

- Antoniou, S. [2002] "Advanced inelastic static analysis for seismic assessment of structures," *PhD Thesis*, Imperial College London, University of London, United Kingdom.
- Antoniou, S. and Pinho, R. [2004] "Advantages and limitations of adaptive and non-adaptive force-based pushover procedures," *Journal of Earthquake Engineering* **8** (4), 497–522.
- ATC [1997] "NEHRP Guidelines for the seismic rehabilitation of buildings," *FEMA Report No. 273*, Federal Emergency Management Agency, Applied Technology Council, Washington, D.C.
- Calvi, G. M. and Pavese, A. [1995] "Displacement based design of building structures," *Proc. of the Fifth SECED Conference on European Seismic Design Practice*, Chester, United Kingdom, pp. 127–132.
- Hughes, T. J. R. [1987] *The Finite Element Method, Linear Static and Dynamic Finite Element Analysis* (Prentice-Hall, Inc.).
- Kowalsky, M. J., Priestley, M. J. N. and MacRae, G. A. [1995] "Displacement-based design of RC bridge columns in seismic regions," *Earthquake Engineering and Structural Dynamics* **24**(12), 1623–1643.
- Moehle, J. P. [1992] "Displacement-based design of RC structures subjected to earthquakes," *Earthquake Spectra* **8**(3), 403–428.
- Priestley, M. J. N. [1997] "Displacement-based seismic assessment of reinforced concrete buildings," *Journal of Earthquake Engineering* **1**(1), 157–192.
- SeismoSoft [2004] *SeismoStruct — A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures* [online]. Available from URL: <http://www.seismosoft.com>.