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A DISPLACEMENT-BASED ADAPTIVE PUSHOVER FOR SEISMIC ASSESSMENT OF STEEL AND REINFORCED CONCRETE BUILDINGS

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ABSTRACT

A number of recent studies raised doubts on the effectiveness of conventional pushover methods, whereby a constant single-mode incremental force vector is applied to the structure, in estimating the seismic demand/capacity of framed buildings subjected to earthquake action. The latter motivated the recent development and introduction of the so-called Adaptive Pushover methods whereby the loading vector is updated at each analysis step, reflecting the progressive damage accumulation and resulting modification of the modal parameters, that characterise the structural response at increasing loading levels. Within such adaptive framework, the application of a displacement, as opposed to force, incremental loading vector becomes not only feasible, since the latter is updated at each step of the analysis according to the current dynamic characteristics of the structure, but also very appealing, since inline with the present drive for development and code implementation of displacement or, more generally, deformation-based design and assessment methods. Further, such innovative displacement-based pushover algorithm seems to lead to superior response predictions, with little or no additional modelling and computational effort, with respect to conventional pushover procedures.

Introduction

It is unquestionable that nonlinear time-history analysis is the most accurate method for assessing the response of structures subjected to earthquake action. Indeed, any type of static analysis will always be inherently flawed, given the conspicuous absence of time-dependent effects. However, as noted by Goel and Chopra (2005), amongst others, nonlinear time-history analysis is not without its difficulties or drawbacks, particularly for what concerns application within a design office environment.

Firstly, in order to employ dynamic analysis for seismic design/assessment of structures, an ensemble of site-specific ground motions compatible with the seismic hazard spectrum for the site must be simulated. As described by Bommer and Acevedo (2004), amongst others, this is, however, a far from simple task, since seismic design codes feature insufficient or inadequate

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guidance on procedures to either (i) generate artificial spectrum-compatible records, (ii) produce synthetic accelerograms from seismological models or (iii) select appropriate suites of real acceleration time-series, eventually modified to better fit a given code response spectrum. The authors believe that until better guidance on record selection/generation will be made available to earthquake engineer designers, this first step will remain as a very difficult-to-overcome hurdle to the use of dynamic time-history analysis in design office applications.

Secondly, notwithstanding the significant increase in computing power witnessed in recent years, nonlinear time-history analysis remains computationally demanding, especially when fibre-based (distributed inelasticity) structural analysis programs, which are simpler to calibrate than their plastic-hinge (concentrated plasticity) counterparts, are employed to model the seismic response of large multi-storey irregular buildings, requiring 3D models with thousands of elements. This problem becomes even the more significant if one considers that the analyses will need to be repeated a significant amount of times, not only because design codes or guidance documents request for a relatively large number of earthquake records to be employed in order to warrant minimum probabilistic validity of the results, but also, and perhaps mainly, because the process of analysing any given structure is invariably an iterative one, given that modelling errors are commonly encountered as the design/assessment process evolves.

Thirdly, even in those situations where the expertise and resources for running time-history analyses is available, it is often the case that preliminary simpler analysis (i.e. modal and static analyses) are run to enable a first check of the model; errors in the definition/assemblage of a finite elements model are difficult to detect from dynamic analysis results, whilst they tend to be relatively evident from the output of eigenvalue or pushover runs. As an example, inspection of the first modes of vibration of a given building model may be used to check if member and mass has been correctly distributed, whilst examination of a force-displacement monotonic capacity curve may serve to quickly assess if member strength and ductility has been properly assigned. In addition, the explicit insight that pushover-derived base shear vs. top displacement capacity curves provide into the stiffness, strength and ductility of a given structure, constitutes the type of qualitative data that is always most informative and useful, within a design application, even when time-history analysis is then employed for the definitive verifications.

The above constitute, in the opinion of the authors, strong reasons for nonlinear static analysis methods to continue to be developed and improved, so that these tools can become ever more reliable and useful when used either as a replacement to time-history analysis in the seismic design/assessment of relatively simple non-critical structures, or as a complement to dynamic analysis of more complex/critical facilities. It is, therefore, within this framework of warranted development of nonlinear static analysis procedures that the current endeavour finds its justification and rationale.

Definition and Scope of Work

The term ‘pushover analysis’ describes a modern variation of the classical ‘collapse analysis’ method, as fittingly described by Kunnath (2004). It refers to an analysis procedure whereby an incremental-iterative solution of the static equilibrium equations has been carried out to obtain the response of a structure subjected to 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. In this manner, each point in the resulting displacement vs. base shear capacity curve represents an effective and equilibrated stress state of the structure, i.e. a state of deformation that bears a direct correspondence to the applied external force vector.

Recent years have also witnessed the development and introduction of an alternative type of nonlinear static analysis, which involve running multiple pushover analyses separately, each of which corresponding to a given modal distribution, and then estimating the structural response by combining the action effects derived from each of the modal responses (i.e. each displacement-force pair derived from such procedures does not actually correspond to an equilibrated structural stress state). Paret *et al.* (1996) first suggested the Multi-Modal Pushover procedure, which was then refined by Moghadam and Tso (2002). Chopra and Goel (2002), on the other hand, have developed and proposed a Modal Pushover Analysis (MPA) technique, which Hernández-Montes *et al.* (2004) have then adapted into an Energy-based Pushover formulation. A further refinement of such multiple-pushover procedures consists in the employment of adaptive updating of the loading pattern (e.g. De Rue 1998; Gupta and Kunnath, 2000; Aydinoglu 2003), effectively meaning that the methods may now be named as Incremental Response Spectrum Analysis, as eloquently proposed by Aydinoglu (2003). As highlighted by their respective authors, the main advantage of this category of static analysis procedures is that they may be applied using standard readily-available commercial software packages. The associated drawback, however, is that the methods are inevitably more complex than running a single pushover analysis, as noted by Maison (2005), for which reason they do not constitute the scope of the current work, where focus is placed on single-run pushover analysis procedures, that can, notwithstanding their more evolved nature, be easily incorporated in commercial programs.

In tandem with the present drive for performance-based seismic engineering, there is also a thrust 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 increased accuracy potential of such an innovative displacement-based adaptive pushover method (DAP), to estimate the response characteristics of steel and reinforced concrete buildings subjected to earthquake excitation. 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. It is shown that the new approach may yield 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.

Displacement-Based Adaptive Pushover Analysis (DAP)

Traditionally, the *increasing lateral load pattern* used in pushover analysis has always been applied in invariant fashion, effectively implying that the response of a structure is controlled by a single fundamental mode shape that remains unchanged until collapse occurs. At most, two lateral load patterns, namely the first mode proportional and the uniform, were 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 (ATC 2005), 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 Figs. 1 and 2, examples of inadequate prediction of both the capacity curve as well as the deformation response characteristics of a 12-storey frame subjected to a natural earthquake recording (case-study RM15-NR2 in Antoniou and Pinho 2004) and of a 4-storey irregular frame subjected to an artificial accelerogram (ICONS full-scale test specimen, described in Pinho and Elnashai 2000) 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 Fig. 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.

The main reason behind the underperformance of these conventional pushover methods is the fact that they 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

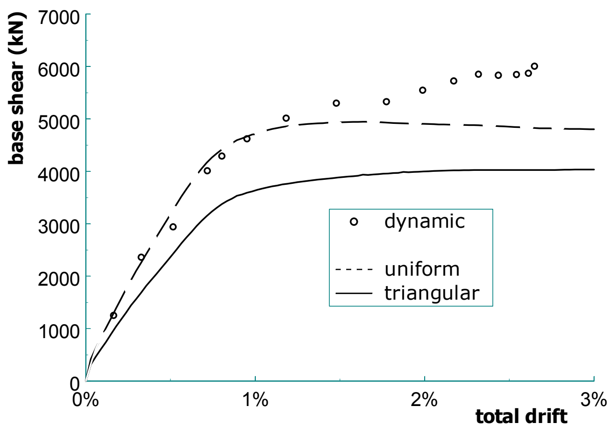
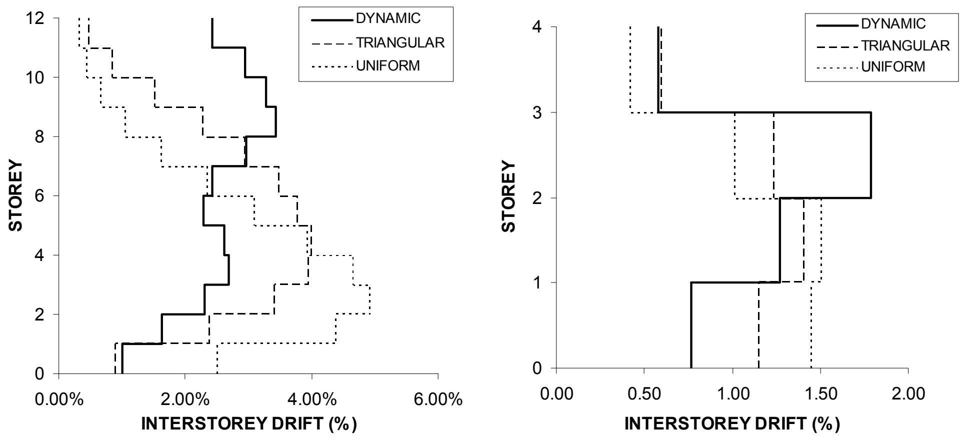


Figure 1. Capacity curves of a 12-storey building, obtained with standard pushover and Incremental Dynamic Analysis



(a) (b)

Figure 2. Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with standard pushover.

elongation of the periods of vibration (Fig. 3), which then, depending on the shape of the response spectrum being considered (or on the frequency content of an input record), may trigger significant changes in the response characteristics of the buildings (Fig. 4). Krawinkler and Seneviratna (1998) 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 (Fig. 5); it is noted that in adaptive pushover the response of the structure is computed in incremental fashion, through piecewise linearisation, as schematically shown in Fig. 6, below.

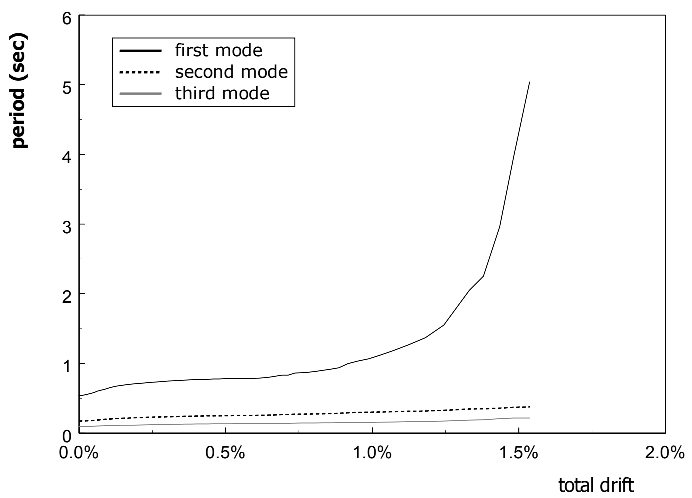


Figure 3. Periods of vibration of 4-storey building under increasing levels of deformation.

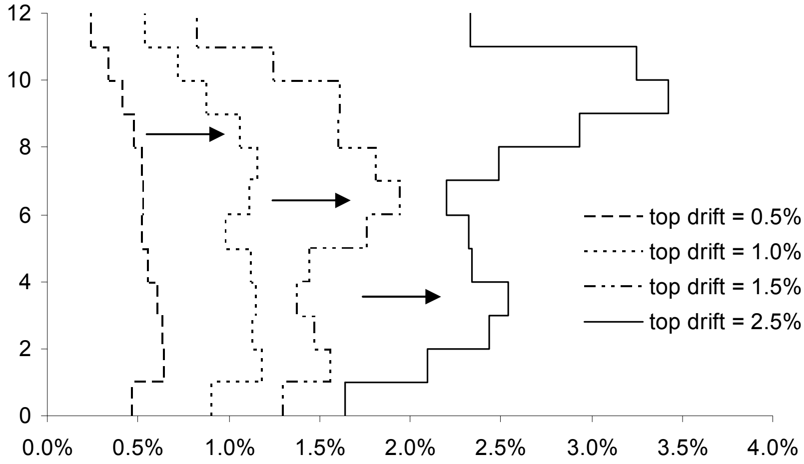


Figure 4. Interstorey drift profiles of a 12-storey building subjected to increasing levels of deformation.

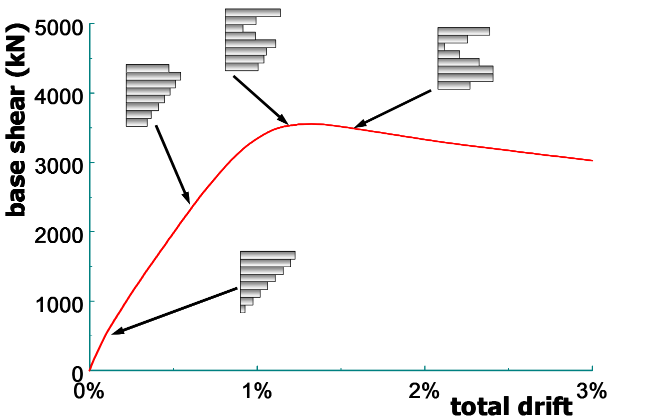


Figure 5. Adaptive pushover: shape of loading vector is updated at each analysis step.

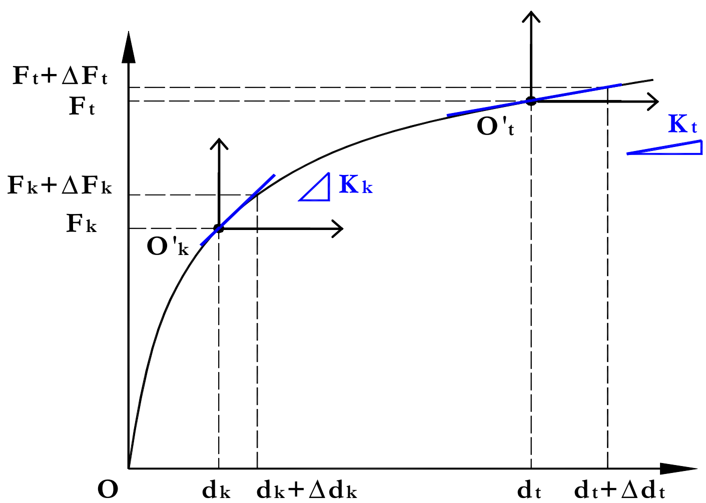


Figure 6. The use of tangent stiffness in updating (i.e. incrementing) the loading vector.

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.

Force-based adaptive pushover procedures have been proposed by Reinhorn (1997), Satyarno *et al.* (1998), Requena and Ayala (2000), Elnashai (2001) and Antoniou *et al.* (2002). With the exception of the work of Satyarno *et al.* (1998), where a single mode adaptive pushover pattern was employed, all other adaptive methodologies considered the effects of the higher modes and of the input frequency content. Furthermore, Elnashai (2001) and Antoniou *et al.* (2002) implemented their adaptive algorithm within a fibre analysis framework, allowing for a continuous, rather than discrete, force distribution update to be carried out. Despite their apparent conceptual superiority, or at least despite their conspicuously more elaborated formulation, the improvements introduced by these Force-based Adaptive Pushover (FAP) procedures was not impressive, with respect to its traditional non-adaptive counterparts, particularly in the estimation of deformation patterns of irregular buildings, which tend to be poorly predicted by both types of analysis. As discussed by a number of researchers (e.g. Kunnath 2004, López-Menjivar 2004), 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.

With a view to overcome the limitations described above, Antoniou and Pinho (2004) 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. The reader is referred to Antoniou and Pinho (2004) for a detailed description of the DAP algorithm.

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 shown in Antoniou and Pinho (2004). 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.

DAP – Case Studies, Modelling and Results

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 structure, designed according to Eurocode 8 (CEN 2002), displayed a highly irregular dynamic behaviour (e.g. Fig. 2(a)) 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. 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 (Pinho and Elnashai 2000) 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. Fig. 2(b)) 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 representing European seismicity.

For what concerns the Finite Elements Analysis package used in the present work, SeismoStruct (Seismosoft 2004), 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. Pinho and Elnashai 2000, Casarotti 2004). Further, the package features also the readily availability of the displacement-based adaptive pushover algorithm employed in this study.

In Fig. 7, 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. In Fig. 8, 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.

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, seems to have the potential to provide accurate predictions, throughout the entire deformation range, of the dynamic response characteristics of irregular building frames. The additional modelling and computational effort requested to run such type of analysis is, with respect to conventional pushover procedures, negligible, as discussed in Antoniou and Pinho (2004). An extensive parametric verification programme is currently underway, to further attest the accuracy of DAP.

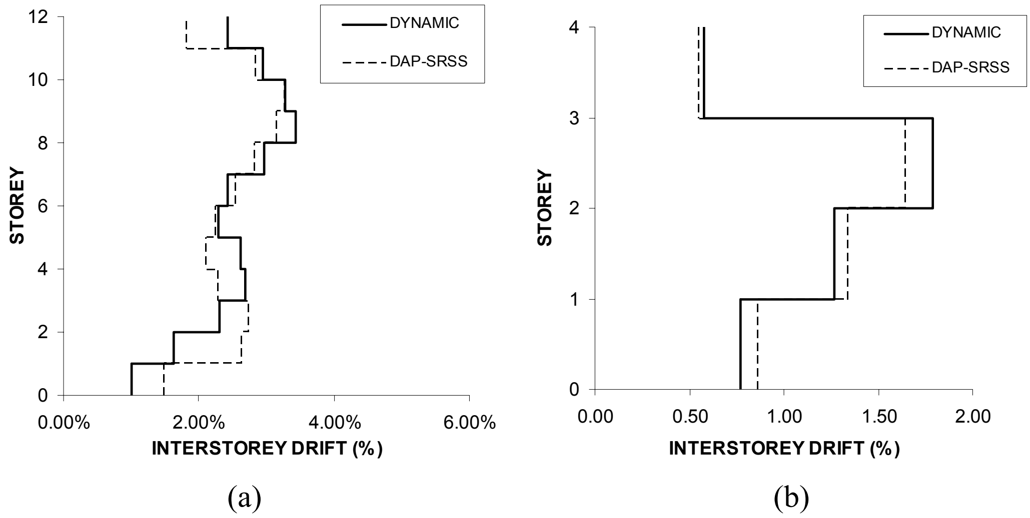


Figure 7. Interstorey drift profiles of (a) 12-storey building and (b) 4-storey irregular frame, obtained with Displacement-based Adaptive Pushover using SRSS combination.

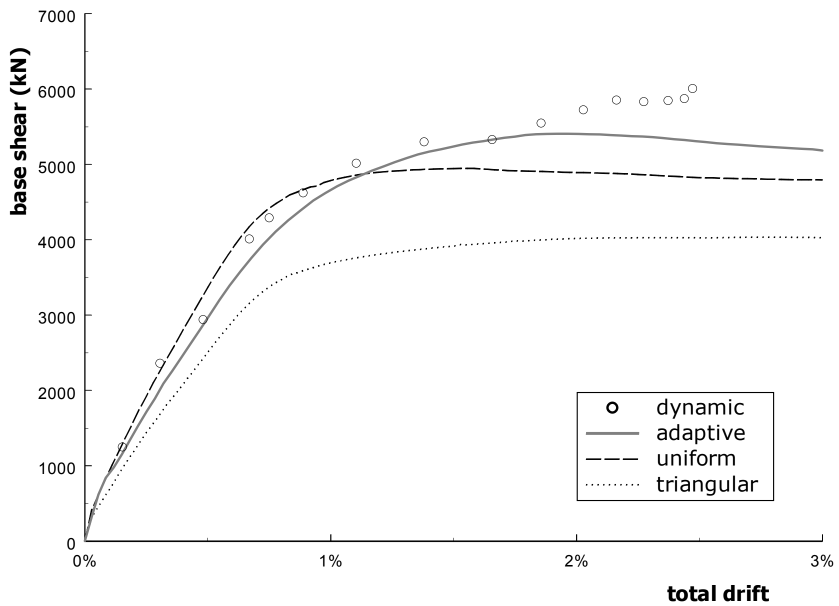


Figure 8. Capacity curves of a 12-storey building, obtained with DAP and standard pushovers, and compared against IDA envelopes.

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