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DEVELOPMENT AND VERIFICATION OF A FULLY ADAPTIVE PUSHOVER PROCEDURE

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ABSTRACT

Inelastic static pushover analysis of structural systems subjected to earthquake loading is rapidly gaining ground as a tool for design and assessment. Whereas the potential of such methods is recognised, especially in contrast with force-based elastic analysis, there have been concerns over their reliability in predicting correctly the inelastic seismic demands. In this study, a new enhanced pushover methodology, which tries to mitigate some of the inherent limitations of static procedures, is proposed. The suggested scheme is fully adaptive and considers the current stiffness state and modal properties of the structure at various levels of inelasticity to update the lateral load distribution along the height. Additionally, site-specific spectra can be taken into account for the scaling of the forces. The integrity of the method is verified through the use of a set of sophisticated structural models, utilising both conventional pushover, as well as inelastic dynamic analysis procedures, for comparison purposes. It is shown that the new approach yields static analysis results very close to inelastic time-history analysis and captures response characteristics that only detailed dynamic analysis could predict. The performance and applicability of the method are commented, and areas for further developments are explored.

Keywords: nonlinear static analysis; adaptive pushover; dynamic pushover; spectral scaling

INTRODUCTION

Whereas the basic characteristics of seismic loading and structural response have been identified in the framework of recent years' research studies, it is clear that this is not followed by a consistent development in everyday design practice. Although sources of inelasticity within a structural system can be identified and, therefore, the inelastic behaviour of a particular structure can be described, the vast majority of design offices remain attached to basic seismic code practices, according to which, a crude modification factor is applied to the elastic forces, in order to account for inelastic behaviour amongst various other phenomena.

Under the pressure of recent developments, seismic codes have begun to explicitly or implicitly require identification of sources of inelasticity and quantification of their energy absorption capacity. Ideally, the performance evaluation of structural systems subjected to earthquake loading should be based on non-linear time history analyses utilizing a set of carefully selected ground motion records. However, the inherent difficulties in the selection of the records, the poor understanding of issues such as viscous, hysteretic and algorithmic damping, the sensitivity of the results to the modelling of the mass distribution of the structure, the complexities in adequately representing the cyclic load-deformation characteristics of all the important structural elements, as well as the additional computational effort required, raise doubts about its suitability in everyday practice. Therefore, only special cases of complex analyses can justify economically the use of inelastic time-history analysis.

As a result, pushover analysis has been gaining significance, as a tool for assessment and design verification. However, it has been shown by many researchers that, despite its efficiency and applicability, its also exhibits significant limitations [1, 2, 3, 4]. For example, the deformation estimates can be highly inaccurate, if higher mode effects are of importance. Moreover, torsional effects are difficult to incorporate, whereas the progressive stiffness degradation, the change of the modal characteristics and the period elongation cannot be modelled. Consequently, the method, as implemented nowadays, has to be used with great care and engineering judgement.

Recently, several attempts have been made to extend the applicability of pushover analysis to account for torsional, higher mode and stiffness degradation effects [5, 6, 7, 8, 9]. Within this framework of continuous improvement of current tools for nonlinear static analysis, Elnashai [10] proposed a new enhanced adaptive pushover procedure, which has now been further developed and tested by the authors of the present work. The suggested procedure is ‘adaptive’, in the sense that the lateral load distribution is constantly updated during the analysis. In this way, the structural stiffness at different deformation levels is considered in the evaluation of the new forces, the system degradation and period elongation can be accounted for and the alteration of the inertia loads during dynamic analysis for different deformation levels may be successfully modelled.

The method is ‘multi-modal’, thus explicitly accounting for higher-mode effects, including spectral amplifications of the different modes (a site-specific spectrum may be utilised for the derivation of the new force patterns). The proposed multi-modal and adaptive pushover analysis, apart from being conceptually more robust, yields static analysis results closer to inelastic time-history analysis than the existing approaches and captures response characteristics and failure mechanisms that only detailed dynamic analysis could predict, even for structures with stiffness and strength irregularities. Overall, it provides a more attractive alternative to dynamic analysis than conventional pushover procedures with fixed patterns.

PROPOSED METHODOLOGY

The new adaptive pushover procedure has been tested and verified using the Finite Element software SeismoStruct [11]. The main advantage of the proposed algorithm is that it permits the application of the exact force profiles calculated by modal analysis at every step, without stability or performance problems. Moreover, it is extremely flexible and it accepts many different options, such as:

- Scale the modal forces with or without the consideration of spectral amplification. With the former, a site-specific analysis can be carried out, whilst with the latter, the procedure is still adaptive, since the force distribution is updated but only according to the modal properties of the structure.
- Introduce a user-defined (usually code-based) spectrum or use a particular record to derive the spectral coordinates.
- Update the load distribution at every step for better accuracy and stability or at predefined steps to reduce the computational effort.
- Scale, according to the current stiffness distribution, only the increment of forces applied at each step ('incremental solution') or the total forces applied to the structure throughout the process up to the current point ('total solution').

The basic steps of the proposed methodology, described in greater detail in the work of Antoniou and Pinho [12], are described below in a summarised fashion:

1. At each step, prior to the application of any additional load, perform eigenvalue analysis considering the stiffness state at the end of the previous load step and calculate the periods and eigenvectors of the system. The highly efficient Lanczos method [13] is used for this purpose.
2. Based on the modal shapes and the participation factors of the eigensolution, the patterns of storey forces are determined separately for each mode. If a spectral shape is considered the corresponding for each mode of vibration is also considered in the computation of force pattern.
3. The lateral load profiles of the modes are combined using either the Square Root of the Sum of Squares (SRSS) or the Complete Quadratic Combination (CQC) method. Since only the relative values of storey forces are of interest (the absolute values are determined by the load factor λ and the nominal loads), the horizontal loads are normalised with respect to the total value.
4. Update (increase) the load factor λ. The forces applied at each storey are evaluated as the product of the updated load factor, the nominal load at that storey and the storey forces obtained above (note that, normally, the nominal loads at all the storeys should be equal, since the effect of the different mass values is accounted for by the eigenvalue procedure). If incremental scaling is applied, only the load increment is updated, and then added to the load at the previous step.
5. Apply the new calculated forces to the model and solve the system of equations to obtain the structural response at the new equilibrium state.
6. Calculate the updated tangent stiffness matrix of the structure and return to step one of the algorithm, for the next step of the adaptive pushover analysis.

Not surprisingly, each variation of the algorithm yields different results. However, the solution with incremental scaling and inclusion of spectral amplification was proven to be superior to all the other alternatives, in terms of accuracy, maintaining also its numerical stability.

Overall, the proposed algorithm is simple and can easily be implemented in any analytical package. It provides an efficient and stable solution, which is expected to perform better than any pushover procedure with a fixed force pattern, and certainly compensates for the practical negligible additional time required.

VERIFICATION

Adaptive pushover is intended to be a method for general use in design and assessment. It is, therefore, imperative to verify its efficiency for different structural configurations and heights but also for input ground motions with different dynamic characteristics. Hence, a series of frame systems were considered and analysed, using conventional procedures as well as the suggested methodology. Furthermore, to assess the method's efficiency, a considerable amount of dynamic analyses were conducted and the corresponding results were compared with those from adaptive pushover.

The three different structural configurations used in order to identify the efficiency of the method, consist of a twelve storey regular frame, an eight storey irregular frame and a dual (wall-frame) system. Moreover, different ductility classes and design ground accelerations were considered, resulting in a total of six structural models. The models represent common reinforced concrete structures and are based on buildings designed and detailed at the University of Patras [14], according to Eurocode 8, Parts 1-1 to 1-3. Subsequently, they were modelled by Mwafy [15] under the framework of a different project, and were then adapted by Rovithakis [16] for the purpose of the current project. Their general characteristics are defined in Table 1 and schematically illustrated in Figure 1.

TABLE 1

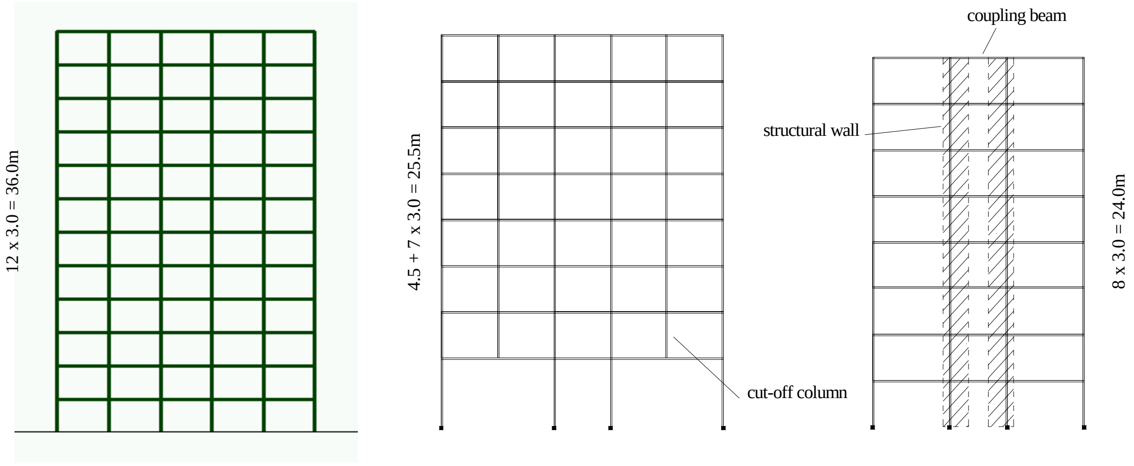
DEFINITION OF THE STRUCTURAL SYSTEMS CONSIDERED

Group	Structure reference	Structural system	No. of storeys	Ductility level	$T_{elastic}$ (sec)
1	I8H30	Irregular frame	8	High	0.674
	I8L15			Low	0.723
2	R12H30	Regular frame	12	High	0.857
	R12L15			Low	0.913
3	W8H30	Regular frame-wall	8	High	0.538
	W8L15			Low	0.588

Moreover, a set of one artificially-generated and two natural records were employed for the time-history analyses of the study, resulting in a total number of 6×3=18 cases. The synthetic signal was generated to represent a typical earthquake of the Mediterranean region with a return period of 975 years [17], corresponding to modern codes demand. The two natural input motions were recorded at the Loma Prieta earthquake (California, USA, 17/10/1989, M = 7.1). The elastic response spectra of the records for an equivalent viscous damping of 5% are shown in Figure 2.

Finally, for each structural system, two conventional and eight adaptive pushover analyses were run. For the former, use was made of the code-specified inverted triangular and uniform load patterns, whilst for the latter, the following cases were considered:

(i) adaptive pushover with total scaling and without spectral amplification;
(ii) adaptive pushover with incremental scaling and without spectral amplification;



REGULAR SYSTEM IRREGULAR SYSTEM DUAL SYSTEM

Figure 1: Geometric characteristics for regular, irregular and dual systems

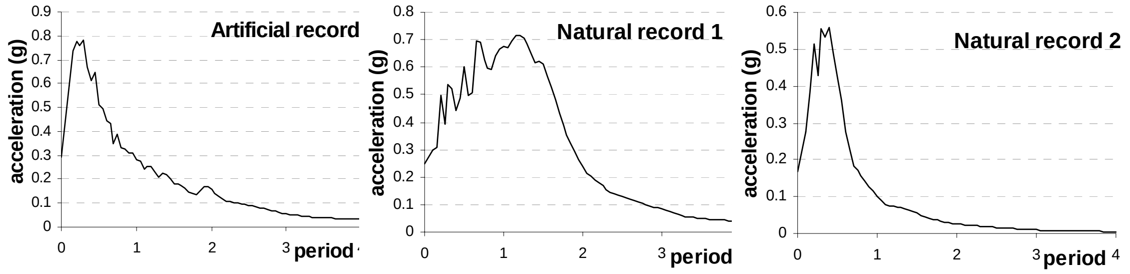


Figure 2: Response spectra of the input ground-motion

(iii) adaptive pushover with total scaling and spectral amplification for all three records;
(iv) adaptive pushover with incremental scaling and spectral amplification for all three records.

The results of the pushover procedures were then compared to the envelopes derived with the recently proposed ‘incremental dynamic pushover procedure’ [15, 18, 19, 20].

Period Elongation, Spectral Amplification and Force Distribution

The basic feature of the adaptive pushover algorithm is the redistribution of the storey forces, according to the modal properties at each step. In this manner, the system’s progressive degradation, as a consequence of the inelastic deformations, can be efficiently modelled. During the adaptive pushover procedure, the periods elongate significantly (up to 10 times the linear elastic values in some cases), once yielding of the structural system has occurred. This is a typical pattern followed in all the adaptive pushover procedures, with the most significant changes occurring for the values of the fundamental period.

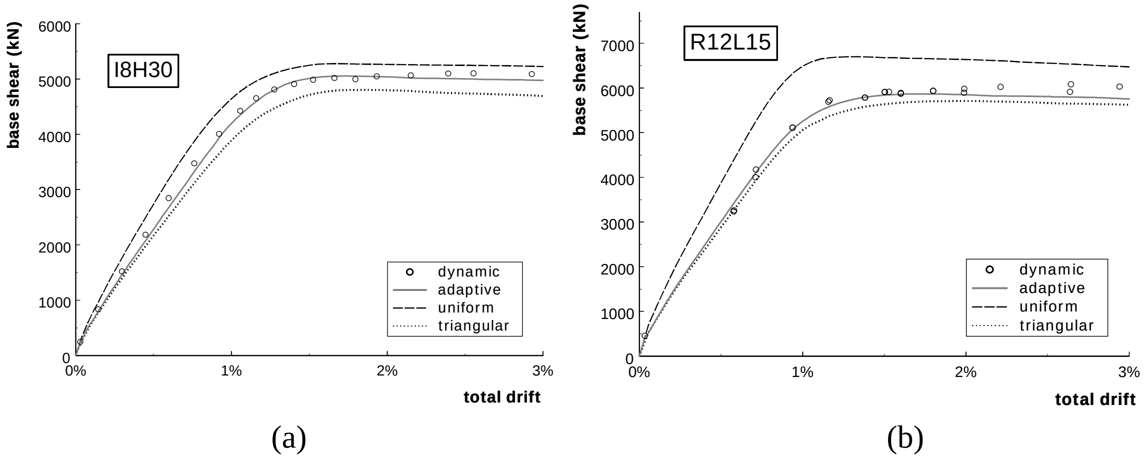
This considerable and rapid increase in the periods significantly affects the spectral amplifications of the modes, resulting in completely different values of spectral response at the beginning and the end of the process. Moreover, the shape of the modes is continuously altered for different degrees of inelasticity. This change in the modal characteristics and the spectral amplifications is directly reflected to the applied force distribution.

In general, the forces start from triangular or trapezoidal-like shape, determined by the elastic characteristics of the system and the corresponding spectral coordinates. Throughout the elastic range, the stiffness matrix is essentially constant and, therefore, the force pattern remains unaffected. Note that this means that the relative values of the forces are not altered, but the absolute values, which are determined by the load factor, are continuously updated. With the onset of significant structural damage, the stiffness state of the model is modified, resulting in the change of the forces shape. With the increase of the deformation level, further changes in the stiffness matrix result in changes of the load distribution shifting it to more uniform patterns, which mean that the damage has been concentrated at a specific location, favouring a pattern similar to a SDOF system.

Base Shear vs. Top Displacement Curves

The basic objective of the pushover analysis is to derive the base shear versus top displacement curve. This can provide important features of structural response, such as the initial stiffness of the structure, the total strength and the yield displacement and the post-peak behaviour. It is therefore of crucial importance to examine the accuracy of the new method, in terms of the base shear vs. top displacement curve, by comparing it to dynamic analysis envelopes. The objective of the aforementioned comparison is twofold. Firstly, to identify the differences in the results obtained by different variations of the method and secondly to investigate its accuracy, compared to the accuracy of conventional pushover procedures with fixed load distributions.

In Figure 3, the curves for one irregular and one regular structural system are presented. Whereas the conventional static methods were found inadequate to capture the characteristics of the dynamic behaviour, the adaptive curves for the models with strength irregularities provided an outstanding fit to the dynamic envelopes. Both cases verify the statement of gradual shift of the load distribution from an almost triangular to a more uniform pattern. As expected from their definition, fixed load distributions failed to capture such a feature, which has been captured by the adaptive scheme.



(a) (b)

Figure 3: Adaptive vs. conventional procedures: (a) Irregular, high ductility system; (b) Regular, low ductility system

Another interesting observation of the current study was that the uniform and triangular distributions did not always provide an upper and lower bound for the structural response. The dynamic envelope plotted in Figure 4 highlights the case of overestimation (though not significant in this case) of the structural resistance from the conventional static procedures. At least for the elastic and early inelastic range, the triangular force distribution, which was supposed to provide the lower bound, yielded resistance estimates slightly higher than dynamic analyses. What is impressive is that the proposed adaptive scheme yielded better results even in this case, by providing a curve lying slightly lower than the triangular distribution.

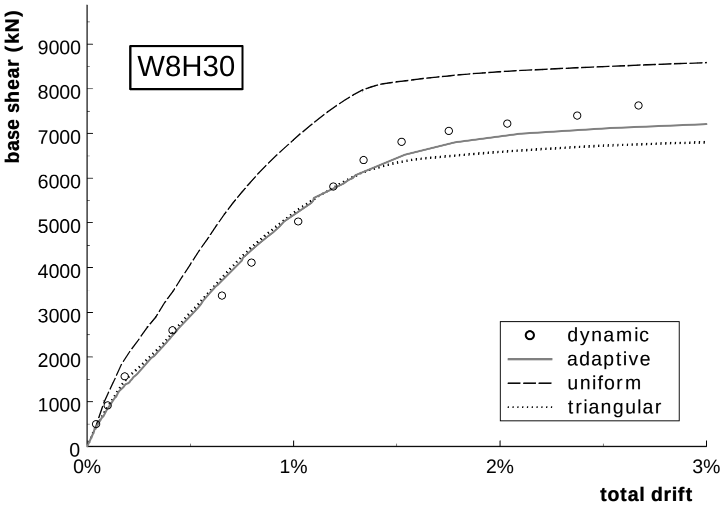


Figure 4: Adaptive vs. conventional procedures for a the dual, high ductility system

Nevertheless, there have been cases, where neither the conventional nor the adaptive pushover schemes managed to reproduce the dynamic envelope results, a behaviour that may be attributed to two main factors. Firstly, the sensitivity of the structural response to the peculiarities of each earthquake record, which can cause irregular, erratic-shaped dynamic envelopes. Secondly, and most importantly, the difficulties faced by static procedures, even by the more sophisticated adaptive schemes, to describe complex dynamic phenomena.

Notwithstanding the few exceptions just mentioned, the main observation of this study has been the significantly improved performance of adaptive pushover when compared to its conventional counterparts. This superiority has been demonstrated in the vast majority of the 18 cases that have been analysed, where the ability of the adaptive scheme to capture phenomena undetectable by conventional pushover procedures has been established.

Ease-of-use, duration and stability aspects

Being a refinement of the well-established pushover analysis with fixed force patterns, the suggested adaptive method should by no means be more difficult to implement than its conventional counterpart. After all, a static procedure that is hard or time-consuming to use would undermine its basic purpose, which is to provide a rather accurate but, above all, simple tool for everyday practice. Considerable effort has been put this end and, consequently, the suggested method requires nothing more but the modelling of the mass distribution of the structure, needed by the eigen-solver.

Furthermore, considering the simplified nature of the approach, the duration of the analysis and the stability of the method are important issues worthy of consideration. Generally, the amount of time necessary 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 can 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.

The utilisation of adaptive, rather than fixed-pattern, pushover procedures requires insignificant additional effort from the user and slightly increased time for the analysis. Considering the conceptual superiority of the new method and its increased accuracy, as well as the rapid increase in the available computational power, it can be asserted that these drawbacks are minor compared to the advantages gained and, therefore, the utilisation of adaptive procedures is strongly recommended.

CONCLUSIONS

A new adaptive pushover algorithm has been proposed, which is intended to be a significant enhancement of existing non-linear static methods. It accounts for higher mode effects, redistributions of forces due to progressive damage accumulation, as well as the expected ground motion. It permits the frequent updating of the applied force distribution, according to a predefined spectral shape and the modal properties of the system at every step, keeping the simplicity and the stability of ordinary pushover procedures. In order to verify the efficiency of the new method and assess its accuracy, a comparative study has been carried out utilising a set of structural models with different configurations and a set of records with diverse dynamic characteristics.

The different variations of the new method provided a much closer fit to the envelopes derived by dynamic analysis than fixed-pattern pushover procedures with different force distributions, in the vast majority of cases examined. It yielded more accurate estimates of the structural response, and it was able to capture phenomena that procedures with fixed load distributions failed to predict. Usually, the profile of the applied load vector varied between triangular or trapezoidal shapes in the early stages of the adaptive analyses and more uniform distributions in the highly inelastic range, as damage was concentrated to a particular location.

Finally, considering the large size of the models employed in the study, it is a definite conclusion that the increase of analysis duration due to the continuous recalculation of the loading vector is insignificant, considering the improvements in the accuracy of the results that it provides, whereas all the variations of the method exhibited remarkable stability.

There have been instances, however, where neither the conventional nor the adaptive pushover schemes managed to reproduce the dynamic envelope results, for the reasons identified in the body of the paper. The use of displacement-based adaptive pushover, not explored in the current presentation, seems to constitute the best solution to overcome such difficulties, as demonstrated by Antoniou and Pinho [21].

Further, the extension of the applicability of adaptive patterns to both horizontal dimensions, for nonlinear static analysis of structures in the 3-D space, represents also another logical step forward within the current research framework. As shown by Pinho and Antoniou [22], such solution may provide an extremely simple and accurate tool for analysing structures where torsion effects might be of significance.

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