AN INNOVATIVE DISPLACEMENT-BASED ADAPTIVE PUSHOVER ALGORITHM FOR ASSESSMENT OF BUILDINGS AND BRIDGES

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According to recently introduced code provisions, such as FEMA-356 (BCCS, 2000) and Eurocode 8 (CEN 2002), 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, well summarised in the FEMA-440 (ATC, 2005) report, rise significant 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. 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.

The aforementioned problems may constitute the reason of the unsatisfactory estimates of the seismic demands by current force-based pushover methods, mainly in irregular structures, due to the fact that the force control does not necessarily represent the actual dynamic response, as the

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distribution of forces in a dynamic analysis, even with a dominant first mode, do not exhibit a constant multiplier when inelastic mechanisms are activated. On the other hand, it is commonly agreed that the application of a constant displacement profile would force a predetermined and possibly inappropriate response mode, concealing important structural characteristics and concentrated inelastic mechanisms at a given location. As a result, recent years have witnessed the introduction of the so-called adaptive pushover methods, which feature the ability to account for the effect that higher modes of vibration and progressive stiffness degradation might have on the distribution of seismic forces: the latter near collapse may differ significantly to that at the start of the analysis. The additional modelling and computational effort, with respect to conventional pushover procedures, is negligible. The recent development of adaptive procedures led to an improvement of the agreement between static and dynamic analysis, thank 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.

Adaptive procedures have been proposed by Bracci et al. (1997), Sasaki et al. (1998), Matsumori et al. (1999), Gupta and Kunnath (2000), Requena and Ayala (2000), Elnashai (2001), Aydinoglu (2003). The methodologies elaborated by latter three are conceptually identical, with the difference that Elnashai implemented the procedure within a fibre analysis framework, allowing for a continuous, rather than discrete, force distribution update to be carried out. An adaptive load profile has the advantage of loading the structure according to its current dynamic characteristics at each step of the analysis, but despite its conceptual superiority, current force-based adaptive pushover features a relatively minor advantage over its traditional non-adaptive counterpart, particularly in what concerns the estimation of deformation patterns of buildings, which are poorly predicted by both types of analysis. 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: currently implemented 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 way of overcoming such difficulty is the employment of a displacement loading profile, entirely feasible within an adaptive pushover framework, since a displacement-based algorithm allows the possibility of introducing the reversal of at least the shear distributions, as a result of the structural equilibrium to the applied displacement pattern (Figure 1). In this manner, not only the pushover analysis leads to more accurate results (deformation profiles and capacity curves) but it also 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.

![Figure 1. Storey shear distribution for a 12-storey building subjected to pushover analyses using (i) constant uniform force, (ii) constant triangular force and (iii) adaptive displacement loading vectors (Antoniou and Pinho, 2004)](image-url)
In the current work, the innovative displacement-based adaptive pushover procedure (DAP) proposed by Antoniou and Pinho (2004) is assessed through an extensive comparative study involving different pushover methods, either single or multi mode, adaptive or conventional, and dynamic nonlinear analysis of reinforced concrete buildings and bridges subjected to diverse acceleration records. The deemed “true” dynamic response has been determined with the envelopes derived from the recent Incremental Dynamic Analysis procedure (Vamvatsikos and Cornell, 2002), whereby a structure is subjected to a series of nonlinear time-history analysis of increasing intensity.

In case of buildings, the new approach manages to provide much improved response predictions, throughout the entire deformation range, in comparison to those obtained by force-based methods: prediction of the global behaviour, as well as of the deformed shape, proved to be very effective. In the case of bridges, DAP also lead to satisfactory results, both in terms of total base shear and of inelastic displacement pattern. Of equally noteworthy status is perhaps the fact that the proposed adaptive pushover schemes are as simple to use as standard pushover methods and have been implemented in an Internet-downloadable Finite Element program, adequate for general usage, and thus rendering the presented analytical methodologies readily available to the practising and research communities.

It is important to observe that a static procedure will never be able to completely replace a dynamic analysis; nevertheless, a methodology is searched to obtain response information reasonably close to that predicted by the nonlinear time history analyses. The innovative displacement-based adaptive pushover method is therefore shown to constitute an extremely 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: simplified performance-based assessment and design procedures can be defined, where the use of adaptive pushover is explicitly or implicitly included.

References


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Keywords: displacement based; pushover algorithm; assessment; buildings; bridges; adaptive load profile