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Dynamic-based pushover analysis for one-way plan-asymmetric buildings

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ABSTRACT

A simple Dynamic-based Pushover analysis for Plan Asymmetric buildings (DPPA) is proposed with the aim of properly considering the effects of torsional behavior as well as the higher modes in the applied lateral load pattern. According to the proposed method, the peak story drifts obtained from the response spectrum analysis (RSA) can be resolved into their translational and rotational components, and the related equivalent static lateral forces and torsional moments can be calculated. Consequently, for accurate estimation of the maximum drift demands of plan-asymmetric buildings, it is proposed that the drift responses obtained from the RSA for the stiff and flexible edges of the building be utilized to construct two lateral-torsional load patterns for nonlinear static analyses. The envelope of the results of two pushover analyses using the constructed load patterns is considered as the seismic demands of the building structure. The target displacement for the pushover analyses can be calculated using the available codes such as ASCE 41-13 with a suggested modification factor. Using a number of structural models, the versatility of the proposed DPPA procedure in estimating their seismic demands is demonstrated by comparison of the obtained results with those calculated from nonlinear time history analysis (NL-THA) and other well –known pushover procedures such as the practical modal pushover analysis (PMPA) and the extended-N2 methods. The comparison of the results clearly demonstrates the efficiency of the proposed DPPA procedure in accurately capturing the response parameters, especially in shear-building structures. Also, it is more applicable and much easier to use in practical structural designs in comparison to other available enhanced pushover procedures.

1. Introduction

Prevalence of irregular structures motivated the researchers to investigate the effects of various irregularities on the response of building structures more precisely. Considering issues related to the distribution of mass, stiffness and strength in the buildings, both in plan and in elevation, design codes have attempted to define the concept of different irregularities. On the other hand, shifting from the elastic to inelastic range of behavior in building structures causes the parametric dependence of the problem to become more complex and less analytically clear. The nonlinear static procedures (NSPs) have been developed for the seismic assessment of structures whose behavior are primarily translational. So, In-plan irregularity appears to have the most adverse effects on the applicability of these procedures in accurately estimating their seismic-induced response parameters. In recent years, various attempts have been made to extend the NSPs to plan asymmetric buildings in which the effect of their torsional modes is considerable. Therefore, for these buildings in which the first translational mode is not an adequate representative of a complex structural system, the conventional NSP is not a reliable method to estimate the structural demands. On the other hand, the code specifications still do not provide clear and specific guidelines for the seismic analysis of such structures. In the following, a brief review of enhanced pushover procedures for estimating the seismic demands in asymmetric buildings is presented.

1.1. Enhanced pushover procedures

The current techniques to improve the NSP are trying to efficiently address two issues which cannot be properly identified with conventional pushover analyses: (i) the contribution of higher and torsional modes to consider the effects of the vertical and in-plan irregularities, (ii) the effects of the nonlinearity extent, stiffness degradation and changes in the dynamic properties of the structural systems related to the progressive damage. The modal pushover procedures, the enhanced NSPs with linear dynamic analysis, and the procedures with corrective eccentricities have focused on first issue while the adaptive and multiphase pushovers mainly consider the second issue. The large amount of studies has not yet led to specific conclusions and the seismic codes and

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guidelines do not explicitly suggest the improved NSPs in their specifications. Instead, they prefer to impose limitation on using NSPs. In the following, some of the recently developed NSPs are briefly presented.

1.2. Modal pushover procedures

Paret et al. [1] introduced the multi-modal pushover (MMP) method in which the structure's capacity for each mode is compared with the seismic induced demands using the capacity spectrum method (CSM). Chopra and Goel [2] developed a similar approach known as modal pushover analysis (MPA), in which several independent pushover analyses are carried out, considering different load patterns associated with different mode shapes. More specifically, in case of structures with plan irregularities the method involves the application of both lateral forces and torques at each story level [3]. The results are then combined using the SRSS or CQC rules. In a later work, Chopra et al. [4] proposed the modified modal pushover analysis (MMPA) in which the inelastic response associated to the first mode is combined with the elastic contribution of higher modes. Goel and Chopra [5] described an improved version of the MPA, which requires the estimation of plastic hinge rotation on the basis of the estimated inter-story drift and an assumed inelastic mechanism. Further developments are provided by Reyes and Chopra [6,7] that extended the method to 3-D eccentric buildings subjected to bi-directional excitations and defined the practical modal pushover analysis (PMPA). Also, they proposed to estimate the seismic demands directly from the elastic design spectrum without performing any nonlinear dynamic analysis (NLDA) of the modal single degree of freedom (SDOF) systems for each ground motion, thus avoiding the complications of selecting and scaling ground motions.

Hernández-Montes et al. [8] developed an energy-based pushover technique that overcomes the shortcomings of original MPA through sign reversals of the higher-mode effects. Rofooei et al. [9] introduced modal spectra combination method in which the modal load patterns combined with spectra-based formulation to produce the proposed load pattern. Fujii [10] proposed the pushover analysis for asymmetric buildings under bi-directional excitation in which the final response determined as the sum of the results of pushover analyses with the first two modes load patterns performed in the proper directions.

1.3. The NSPs modified with linear dynamic analysis

In these procedures, the results of linear dynamic analysis, e.g., response spectrum analysis (RSA), are used beside the pushover analysis, and the effects of torsion and higher modes are considered with amplifications and reductions of pushover results based on RSA responses. In that regard, Moghadam and Tso [11] defined a pushover procedure based on elastic response spectrum analysis. Penelis and Kappos [12] proposed the equivalent load vector derived from translational and torsional displacements that are obtained from RSA. Ayala and Tavera [13] applied the lateral load and torsional torque determined from RSA and generated the base shear force and the base torque versus roof displacement/rotation curves for the equivalent SDOF systems. Fajfar et al. [14,15] proposed the extended version of the N2 method which is particularly developed for plan irregular building structures. In this method, the torsional amplification of lateral displacements is suggested with a corrective factor that is computed as the ratio of the normalized displacement obtained from a linear RSA to that of the pushover analysis. Later, the incremental N2 method is proposed as an alternative to incremental dynamic analysis (IDA) to investigate the effect of seismic intensity [16] on the perfromance of the method. Recently the extended N2 method has been improved to take into account the higher modes effects both in plan and elevation [17,18]. The same procedure is introduced as an extension of the conventional CSM-FEMA440 method which uses the extended N2 technique to consider the torsional effects in plan-asymmetric buildings [19]. Hsiao et al. [20] proposed a procedure based on the extended N2 method with four modifications that account for the target displacement, story drift ratio and the higher mode effects in elevation and plan. Recently, Mirjalili and Rofooei [21] proposed the modified dynamic-based pushover analysis (MDP) in which the load patterns are based on the story drift responses obtained from response spectrum analysis. They also suggested a nonlinearity modification factor based on the lateral story stiffness values at the start and end of pushover analysis.

1.4. Adaptive pushover procedures

These procedures attempt to update the load vectors progressively to take into account the change in the modal properties of the system during the inelastic phase of structural response. The adaptive spectra based pushover [22], advanced pushover analysis [23], adaptive displacement based pushover procedure [24], adaptive modal combination [25], adaptive pushover analysis [26], adaptive modal pushover procedure [27] and adaptive capacity spectrum method [28] are among the adaptive procedures introduced in recent years.

1.5. Procedures with corrective eccentricities

In these methods, the equivalent plan eccentricity is introduced based on dynamic properties and the extent of the nonlinearity of the structural system. In that regard, Ghersi and Rossi [29] and Calderoni et al. [30] introduced the equivalent eccentricity comparing the static and modal analyses. Ghersi et al. [31] and Bosco et al. [32] have used the "corrective eccentricities" related to the elastic and inelastic parameters in their proposed procedures for evaluating the nonlinear asymmetric models. Lin et al. [33] investigated the effect of modal eccentricities in asymmetric-plan buildings and showed that the modal eccentricities, rather than the overall structural eccentricities, are the critical parameters for torsional behavior of structure.

1.6. Multi phases pushover analyses

These procedures are proposed with the aim of utilizing non-constant load patterns in a pushover analyses. For this purpose, pushing the structure is performed in multi phases. In each phase the analysis is done using specific load pattern. Jingjiang et al. [34] proposed a two phase pushover procedure which starts with an inverted triangular load pattern that changes to a $(x/H)^{\alpha}$ form after reaching to a certain level of target displacement. Poursha et al. [35] suggested the consecutive modal pushover (CMP) procedure in which pushover analyses are consecutively conducted in multi phases with force distributions proportional to the mode shapes.

1.7. Seismic codes suggested procedures

Various guidelines and seismic codes for existing buildings have had different suggestions on NSPs application in recent years. The FEMA356 [36] required two separate nonlinear static analyses. The first pushover analysis used a load pattern that was selected from the code suggested elastic force distribution, first mode shape, or story force distribution obtained from SRSS combination of modal story shear responses. The second pushover utilized one of the uniform or adaptive load patterns. The primary recommendation in ATC-40 [37] for load vectors was to use the first mode shape which is generally valid for structures with fundamental periods up to about one second. In FEMA440 [38], ASCE41-06 [39] and ASCE41-13 [40], a single first-mode proportion load pattern was considered sufficient to estimate the response quantities that are not significantly affected by higher modes. FEMA440