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Applicability of the N2, extended N2 and modal pushover analysis methods for the seismic evaluation of base-isolated building frames with lead rubber bearings (LRBs)

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A B S T R A C T

In the recent investigations, the pushover analysis has been mainly used for the seismic evaluation of fixed-base structures, whereas a limited number of research investigations have focused on the applicability of pushover analysis to base-isolated buildings. Therefore, this study attempts to extend the modal pushover analysis (MPA) and the extended N2 (EN2) method to medium-rise base-isolated building frames to account for the effect of higher modes in predicting the seismic demands of these structures. Since the displacement at the isolation level and subsequently the effective stiffness of the isolation system are not predetermined at first, an iterative process was used to fulfill the MPA method for base-isolated frames. The original N2 method, which was recently extended to base-isolated buildings, was also implemented with three different lateral load distributions, i.e. the inverted triangular, the first mode and the PSC load patterns. For this purpose, two steel moment-resisting building frames including low-rise (3-storey) and medium-rise (12-storey) ones were considered. The structures were isolated with lead rubber bearing (LRB) isolation systems. Three types of isolators with different stiffnesses including the hard (H), normal (N) and soft (S) isolators were selected. It was observed that N2 method with the PSC load distribution, in most cases, gives better estimates of the seismic demands for low-rise base-isolated frames. Also, the MPA and the EN2 methods can result in accurate estimates of the seismic demands for medium-rise base-isolated frames with the hard type isolators, but their accuracy deteriorates with the increase in the damping and decrease in the stiffness of isolators.

1. Introduction

The non-linear dynamic analysis is known as the most robust and accurate method for the seismic demand evaluation of structures. However, due to its complexity and computational cost, the nonlinear static method, based on pushover analysis, is increasingly used worldwide. The pushover analysis can provide useful information about the non-linear behavior of structures, locations of plastic hinge formation and redistribution of inertia forces that they can not be obtained through a linear elastic analysis method [1–3]. Therefore, this type of analyses is used as a standard tool in the guidelines (FEMA 356 and ATC 40) to evaluate the seismic performance of existing buildings and to verify the seismic design of new buildings and it has become a popular method in the structural engineering community due to its simplicity. In a pushover analysis, the structure is subjected to monotonically increasing lateral forces with an invariant distribution along the height, until a predetermined target displacement is reached. There are different methods to determine the target displacement, including the capacity spectrum method (CSM) [4], the N2 method [5] and displacement coefficient method (DCM) [6]. On the other hand, this analysis method suffers several limitations. The pushover analysis presumes that the structural response is controlled by a single mode of vibration in which its mode shape remains constant [7]. Though these assumptions are approximate after the structure deforms into the inelastic region, several studies have indicated that these assumptions result in relatively good estimates of seismic demands for multi-degree-of-freedom (MDOF) systems, provided that the fundamental mode of vibration becomes predominate in structural responses [7].

To overcome such limitations, enhanced pushover analysis methods were developed in which the effects of higher modes and changes in the modal properties after the yielding of the structure were taken into consideration. To take the effect of higher modes into account, several methods such as the modal pushover analysis [8], modified modal pushover analysis (MMPA) [9], upper-bond pushover [10], mass proportional pushover procedure (MPP) [11], consecutive modal pushover (CMP) [12], generalized pushover analysis (GPA) [13], the

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extended N2 method [14] and single-run multi-mode pushover analysis [15] were developed. In these methods, to keep the simplicity of the conventional pushover analysis method, a constant lateral load pattern was used through the whole analysis. Also, to consider the effects of higher modes, the modal properties of the structure were used to obtain the constant lateral force distribution. Chopra and Goel [8] developed the modal pushover analysis in which pushover analyses are individually performed for several modes and the modal responses are combined using an appropriate combination rule to calculate the seismic demands such as displacements and storey drifts. The MPA method has the ability to accurately estimate the displacements and storey drifts but does not give satisfactory estimates of plastic hinge rotations [16]. Another study showed that the MPA method is reliable in predicting the seismic demands of the SAC buildings [17]. Chopra et al. [9] proposed the modified modal pushover analysis (MMPA) in which the response contributions of higher vibration modes are obtained with the assumption that the building remains linearly elastic. Jan et al. [10] presented the upper-bound pushover method that the upper-bound of the contribution ratio of the second mode, $(q_2/q_1)_{UB}$, is used in computing the lateral force distribution in which q_n (n = 1,2) is the modal co-ordinate. Kim and Kurama [11] introduced the mass proportional pushover analysis that the effect of higher modes on the lateral displacements is incorporated into a single invariant lateral force distribution which is proportional to the total seismic masses at the floor levels. This method was limited to the estimation of the maximum floor displacement demands and the estimation of other seismic demands was beyond the scope of the method. Poursha et al [12] proposed the consecutive modal pushover (CMP) procedure in which single-stage and multi-stage pushover analyses are used. The multi-stage pushover analysis benefits from the consecutive implementation of the modal pushover analyses that each stage begins with an initial structural state which is the same as the condition at the end of the previous stage. In this method, the seismic responses are determined by enveloping the peak seismic responses obtained from the single and multi-stage pushover analyses. Sucuoglu and Selim Gunay [13] presented the generalized pushover analysis (GPA) method. The method includes several pushover analyses implemented by using the force vectors that are obtained from the modal combination of lateral forces. Recently, the extended N2 (EN2) method [14] was developed to consider the effect of higher modes in estimating the seismic demands. In this method, it is assumed that the structure remains in the elastic range while vibrating in higher modes and the structure's response is estimated by enveloping the results obtained from the pushover analysis and elastic modal analysis. To this end, first, the original N2 pushover analysis and elastic modal analysis are performed. Then, the results obtained from elastic modal analysis are scaled in such a way that the roof displacement would be equal to the roof target displacement obtained from pushover analysis. Finally, the seismic responses obtained by pushover analysis are multiplied by appropriate correction factors that are defined as the ratio between the results derived from elastic modal analysis and the results derived from pushover analysis. Poursha and Amini [15] developed a single-run multi-mode pushover (SMP) analysis method in which the effect of higher modes and the frequency content of ground motions are taken into consideration in the lateral forces without any need to apply a modal combination scheme to the results. In addition to the single-run multi-mode pushover analyses, a single-run conventional pushover analysis with an inverted triangular or a uniform force distribution is implemented. The seismic demands are eventually determined by enveloping the results obtained from the single-run conventional and single-run multi-mode pushover analyses. A non-adaptive displacement-based pushover (NADP) procedure was also developed by Amini and Poursha [18] in which some single-run conventional and enhanced pushover analyses are used. The single-run conventional pushover analysis is implemented using a displacement-based load pattern according to the first mode shape, whereas the single-run enhanced pushover analyses are accomplished by employing the lateral load distributions obtained by combining the modal story displacements. Finally, the seismic demands are determined by enveloping the peak seismic responses derived from the single-run conventional and enhanced pushover analyses.

In addition to the above-mentioned enhanced pushover methods in which the lateral load pattern is kept unchanged during the analysis, adaptive pushover analyses were also developed to consider the effect of changes in the modal properties of a structure on the lateral load distribution when it deforms into the non-linear region [19–23]. In these methods, at each step of analysis, the lateral load distribution is continuously updated according to the modal characteristics of the structure derived by an eigenvalue analysis. The force-based adaptive pushover (FAP) [20], displacement-based adaptive pushover (DAP) [21] and storey shear-based adaptive pushover (SSAP) method [22] fall into the category of adaptive pushover methods.

It should be mentioned that the enhanced pushover analyses have been applied to irregular buildings [24–36] and bridges [37–39] as well.

On the other hand, applying base isolation to engineering structures started in 1960s [40]. In a base-isolated building, the structure is mounted on a material with low lateral stiffness that results in a shift of the fundamental frequency of the structure away from the dominant frequencies of a seismic ground motion. An isolation system provides an additional means of energy dissipation and reduces the transmitted acceleration into the superstructure [41]. Due to the lower value of higher frequencies in the case of a base-isolated structure compared to a fixed-base structure, they play only a minor role in computing the seismic responses. Therefore, the structural responses are basically controlled by the first vibration mode. This characteristic is one of the main assumptions in pushover analysis that seems to be appropriate for base-isolated structures.

Recently, some research investigations have been undertaken to apply pushover analysis to base-isolated building structures [42–44]. Doudumis et al. [42] compared the time history and pushover analysis methods and concluded that there is a good agreement between the values of maximum base shear and maximum roof displacement resulting from the analyses mentioned. Providakis investigated the effect of base isolation system on the seismic performance of steel-concrete composite structures with the aid of pushover analysis method [43]. Kilar and Koren made an attempt to extend the N2 method for base-isolated buildings [44]. Regarding the original version of the N2 Method [45], which was developed by Fajfar and is based on a bilinear idealization of the capacity curve, a tri-linear idealization of the capacity curve was proposed by Kilar and Koren for the seismic behavior of base-isolated structures. The inelastic spectra were derived for the selected single-degree-of-freedom (SDOF) systems with different secondary slopes and damping ratios in the range of interest for base-isolated structures subjected to an ensemble of seven semi-artificial ground motions compatible with the EUROCODE8 target spectrum. In the parametric study, a constant reduction factor was assumed and the corresponding ductility was calculated for different ground motions. It was concluded that the equivalent displacement rule can be applied to base-isolated systems with the proposed non-zero post-yield stiffness. In the second part of their study, a four-storey base-isolated reinforced concrete (RC) building was studied to evaluate the accuracy of the N2 method. It was concluded that the N2 method, in general, provides an acceptable accuracy in the estimation of roof displacement and damage pattern in the superstructure. It is mentioned that the applicability of the N2 method was also studied for asymmetric base-isolated buildings by Koren and Kilar [46]. They concluded that the N2 method can provide reasonable predictions of seismic demands by using a correction factor to account for torsional effects in the case of asymmetric base-isolated buildings.

With regard to the increased use of base isolation systems and little study on the application of pushover analyses, particularly, the enhanced pushover analysis methods to base-isolated buildings, the