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Assessment of proposed lateral load patterns in pushover analysis for base-isolated frames

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ABSTRACT

The effectiveness of two proposed lateral load patterns (LLPs) to estimate the seismic demands of base-isolated building frames by the pushover analysis (POA) is assessed by comparing their estimates with the benchmark responses obtained by the nonlinear time history analysis (NTHA). The proposed LLPs include: (i) pattern derived from the square root of the sum of squares (SRSS) of first three mode shapes of BI frame; and (ii) two variants derived by the modification of the uniform force distribution load pattern. The conventional first mode shape LLP is also used in the POA for the purpose of comparison. A mid-rise (5-storey) and a high-rise (10-storey) base isolated (BI) reinforced concrete building frames are considered as illustrative examples for the analysis. An ensemble of five ground motion time-histories, each of far-field and near-field with forward directivity and fling-step effects are employed for NTHA. Target displacement-based comparison is performed by considering three target displacements, which cater to elastic, elastic to plastic and plastic states on the capacity curve of the building frames. The seismic demands namely, peak storey displacement, maximum inter-storey drift, number of plastic hinges, SRSS of plastic hinge rotations, maximum base shear and maximum isolator displacement are considered for comparison. The study reveals that (i) the errors in estimating the seismic demands by different LLPs depend on the state (elastic or elastic–plastic or plastic) of the building frame in which target displacement is considered; and (ii) the proposed LLP (modified uniform distribution) is found to best estimate the NTHA predictions.

1. Introduction

The nonlinear time history analysis (NTHA) is the most accurate method for seismic evaluation and design verification of building structures. It predicts the inelastic demands with high accuracy in the members of superstructure subjected to different types of earthquakes. Despite its accuracy, NTHA is not a preferred choice as an evaluation tool for the design engineers due to its complexities, such as the requirement of high computation effort, specific ground motion records, proper modeling of members and their stress-strain relationship under cyclic actions [1–3]. These drawbacks led to the development of simpler methods that can predict the inelastic seismic demands in the structure with reasonable accuracy. Hence, the development of the nonlinear static analysis also called the pushover analysis (POA), originated as simplified performance evaluation tool [4,5]. The foundation of the pushover analysis was laid in the 1970s by the research work of Takeda et al. [6], Freeman et al. [7], Freeman [8], and Saiidi and Sozen [9].

Pushover analysis is now accepted as a method for assessing the performance and the design verification of building structures [10,11]. Pushover analysis is also used in the performance-based design to meet the required performance objectives [5,12–16]. A lot of research has been carried out for the development of wide variety of the nonlinear static analysis, considering not only the philosophical concept but also the lateral load patterns to be used in the analysis. The former has given rise to some most commonly used methods namely, the capacity spectrum method (CSM) [17], the coefficient method (CM) [18], the modified CM and the modified CSM [19], and the N2 method [20].

Pushover analysis uses invariant height-wise lateral load distribution pattern to calculate the inelastic seismic demands of the structure which is likely true if the structure is vibrating in a single mode or the fundamental mode. Conversely, when the inelastic deformation takes place in the structure, the identification of the inertial forces and the seismic demands by single lateral load distribution becomes approximate, although it can give conservative results. This lack in the pushover analysis has motivated researchers to develop advanced pushover methods which can consider the contribution of higher modes. Several methods are developed such as, the modal pushover analysis (MPA)

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[21], the modified MPA (MMPA) [22], the upper bound pushover analysis [23], the consecutive modal pushover procedure [24], the extended N2 method [25], the adaptive modal combination (AMC) procedure [26], the extended adaptive capacity spectrum method [27], the displacement-based adaptive pushover (DAP) [28], and the force-based adaptive pushover [29]. Brunesi et al. [30] conducted a valuable study in which the authors conducted high definition finite element analysis of steel moment resisting frames and seismic responses are compared by conventional POA, adaptive POA, and incremental dynamic analysis. Considerable amount of research has targeted the application of the pushover analysis to fixed base structures for which estimation of the seismic demands predicted by the POA was compared with that of the NTHA predictions [1,2,31–34]. Comparisons with the experimental results of shaking table tests have been also performed for fixed-base structures [35].

Conversely, investigations on the applicability of the POA considering different LLPs to base-isolated (BI) buildings are scanty. Kilar and Koren [36,37] evaluated the performance of the 4-storey base-isolated building by the N2 method. They idealized the capacity curve into a tri-linear curve. Three lateral load distributions are considered namely, the triangular, proportional to the first mode shape, and as proposed by the PSC – the protective system committee [38]. The comparison of the results of the N2 method with those of the mean NTHA showed that the N2 method gives good predictions of seismic responses with the PSC load distribution when the structure is slightly damaged. On the other hand, when the structure is highly damaged, the load pattern proportional to the first mode shape gives good estimations. Kilar and Koren [39] applied the extended N2 method [40] considering different load patterns to estimate the effects of torsion on the 4-storey reinforced concrete asymmetric base-isolated building. It was concluded that the extended N2 method provides near predictions to the values obtained by the NTHA for different eccentricities in the superstructure and different locations of the center of isolation systems by the load distribution proportional to the first mode shape. Faal and Poursha [41] compared the applicability of the modal pushover analysis (MPA), the extended N2 method and the N2 method with three load distributions on 3-storey and 12-storey steel moment base-isolated frames. It was observed that the N2 method provides better estimates of the seismic demands and the inelastic effects for the low-rise base-isolated frames. Both load distributions corresponding to the first mode shape and the PSC distribution gave good results. Lee et al. [42] proposed a new formula for the vertical distribution of seismic forces on the base-isolated building. The new formula was derived by combining the fundamental mode shapes of both isolated and fixed base buildings and compared with the distributions as regulated in UBC-91 and UBC-97. A similar approach has been proposed in the so-called 3MM method developed by Cardone et al. [43]. York and Ryan [44] developed improved equations to estimate the distribution of seismic forces in the base-isolated structure considering nonlinearity of the isolation system.

The aforementioned studies assessed pushover analysis for BI buildings, but the investigations were not target displacement specific. Target displacement (peak top storey displacement) specific comparison of responses between the NTHA and the POA has been favored by many investigators [31,45–47] for assessing the effectiveness of the loading patterns of the POA in predicting the nonlinear behavior of fixed base building frames. The reason for this is understandable because:

(i) The designers have fairly a good idea of both design level and extreme level earthquakes in the region where the structure is constructed.
(ii) The designers can make a good guess of the expected peak top storey displacement of the structure with the help of the expected PGA of ground motion and the ductility of the top storey displacement in fixing the target displacement.

These tasks become easier for designers for BI buildings since the isolator displacement primarily governs the target displacement. Because of this reason, a target displacement specific comparison between the POA and the NTHA is performed here for assessing the effectiveness of the proposed load distribution pattern for carrying out the POA.

With this background in view, the objectives of the present study are set to investigate the effectiveness of proposed lateral load patterns used in the POA for evaluating the seismic demands of BI buildings at different target displacements in comparison to the NTHA. The study has the following features:

1. Two new lateral load patterns are proposed in addition to the conventional load pattern which is proportional to the 1st mode shape.
2. The seismic demands estimated by different LLPs are compared with those of the NTHA at three target displacements which conform to three states of the structure namely, elastic state, elastic-plastic state and plastic state as identified on the capacity curve.
3. Effect of different types of earthquakes is considered in the NTHA by taking an ensemble of five time history records of the earthquakes belonging to each category of the far-field, near-field with directivity and fling-step effects.
4. The comparison is made for a number of response parameters namely, peak storey displacement, maximum inter-storey drift, number of plastic hinges, the square root of the sum of squares (SRSS) of maximum plastic hinge rotations, the maximum base shear, and the maximum isolator displacement at a particular target displacement.

Apart from the above features, the present study is characterized by:

(i) Making the comparison with the help of RMS errors in place of mean errors, which tends to even out the differences.
(ii) Including the SRSS of maximum plastic hinge rotations of the superstructure and the maximum base shear in the response quantities of interest for comparison.

The SRSS of maximum plastic hinge rotations of the superstructure denotes the maximum inelastic damage that have taken place at the sections where yielding has occurred. Thus, it is a demand parameter that reflects the maximum inelastic excursions at different yielding sections that structure has undergone during the event of an earthquake.

2. Modeling and design of the frames

Two reinforced concrete buildings with five and ten stories having special moments resisting frames are considered as test examples in this study. The lead rubber bearing isolators are used as base isolation system in both buildings. It is noted that the plan arrangement for the two buildings is equal and symmetric, having six spans in the longitudinal direction and three spans in the transverse direction of equal lengths of 5 m each as shown in Fig. 1(a). The height of each storey is assumed to be 3.2 m for both buildings, giving a total height of 32 m and 16 m to 10-storey and 5-storey buildings. The size of all columns is 650 mm × 650 mm, for 10-storey building; 500 mm × 500 mm, for the 5-storey building. The size of all beams is same, 450 mm × 650 mm, for 10-storey building; 300 mm × 550 mm, for 5-storey building and the thickness of slab for all floors is 150 mm for both buildings.

A typical internal frame in the transverse direction, indicated with red dotted lines in Fig. 1(a), is considered as a test frame for the analysis of both buildings whose elevation view is shown in Fig. 1(b) and (c). A two-dimensional model of the 5-storey and 10-storey test frame for 2-D analysis is created in SAP2000 software, which is widely used for research purposes. The nonlinear behavior of the 2-D frame is modeled by defining the default plastic hinges at the ends of beams and columns.