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A modal shear-based pushover procedure for estimating the seismic demands of tall building structures

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ABSTRACT

Non-linear static procedure (NSP) has been considered as a popular method to predict seismic force and deformation demands for performance evaluation of the structures, in recent years. However, this evaluation tool is restricted to low-rise and regular buildings in which the fundamental vibration mode dominates the structural behavior. Recently, some advanced procedures have been presented to oversee these conventional procedure deficiencies. In the current study, a new nonlinear static procedure considering the effects of higher modes in structural responses is presented. This approach assigns a contribution factor for each mode based on modal shear distribution. The offered contribution factor can be applied for determining the importance of each mode in lateral load pattern formation. In order to verify the results, some other types of pushover-based analysis are also performed and the responses obtained from each NSP are compared with those of rigorous non-linear response history analysis (NL-RHA). Results demonstrated the efficiency of the proposed method in accurate prediction of the seismic demands of high-rise buildings.

1. Introduction

The non-linear static procedure has been suggested as a solution to avoid the difficulties of non-linear dynamic analysis. In pushover procedure, the control node of the structure reaches a predetermined target displacement subjected to monotonically increasing lateral forces with an invariant height-wise distribution [1].

Nowadays, in building codes different lateral load patterns such as uniform, triangular, and first mode distributions are employed. Under these load patterns, the responses are satisfactory for low-rise buildings in which the structural behavior is governed primarily by fundamental mode. However, using the same procedures to estimate seismic demand of high-rise buildings is not suitable as the obtained results suffer from lack of accuracy [2–5]. This may be caused due to various reasons, the most important of which is eliminating the effects of higher modes on the behavior of the structure. Recently, a number of investigations have been conducted to consider the higher mode effects. These efforts have led to development of non-linear static analysis and extension of some valuable techniques [6–16]. One of these advanced methods is the modal pushover analysis (MPA) [2] that is based on structural dynamics theory. In the elastic range, the MPA procedure is equivalent to response spectrum analysis (RSA). A modified modal pushover analysis (MMPA) [17] was then proposed in which the responses of higher modes were calculated by a response spectrum analysis since the responses of the structure subjected to higher mode load vectors are within the elastic range. Multi-mode pushover (MMP) was another pushover-based proposed method [18], in which the seismic demands were not quantified. In pushover results combination (PRC) technique, some pushover analyses were performed using mode shapes as each analysis load pattern. PRC peak responses were obtained using a weighted summation of each pushover analysis results [9]. In 2003, Tysh Shang Jan et al. presented the upper-bound (UB) method based on specific target displacement and lateral load pattern [19]. In this investigation, the contribution ratios of higher modes to the first mode were provided. It was proved that the first two modes had a great contribution ratios and the contribution of higher modes in displacement response could be ignored. Therefore, in upper-bound technique, the proportion of second mode is considered in both lateral load pattern and introduced target displacement. The results revealed that for low-rise buildings conventional procedures (first mode or other FEMA force distributions [20–22]) are more accurate than upper-bound method. In high-rise buildings the upper-bound technique has more reliable performance than conventional methods. In 2015, Poursha et al. presented the modified and extended upper-bound (EUB) pushover procedure. In EUB approach, the seismic demands were modified by enveloping the peak responses of the upper-bound and conventional pushover analyses. In EUB the UB load pattern was extended for the first four modes [23].

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The non-linear static method suggested in Eurocode 8 (EC8) [24] developed by Fajfar et al. [6] provides reasonable results for planar frames. This method, however, in the case of in-plan irregular structures, is not always effective. The main drawback of this method is the lack of accuracy in the estimation of displacement and drift of the stiff edge. To overcome this deficiency, the extended N2 (EN2) method was developed by Kreslin and Fajfar [25]. This method could significantly improve the prediction of floor displacement and story drifts of the stiff side of the building (using correction factors) with respect to the N2 method. In the extended N2, it was assumed that the structure remains in the elastic range while vibrating in higher modes. The elastic modal analysis controlled the results in the upper parts of the building and the pushover responses were relevant for the lower parts in this method [26].

Force-based and displacement-based adaptive pushovers are some other pushover-based methods developed by Antoniou and Pinho [27,28]. In force-based adaptive pushover (FAP), the lateral load pattern was obtained through combining modal story forces for considered modes using SRSS (a statistical method). However, generally, there is no significant difference between the results of adaptive and non-adaptive force-based method [27,29]. Furthermore, it cannot be unnoticed that the results obtained from SRSS always leads to positive values and make the method suffer from lower performance. That is, utilizing SRSS combination rule leads to changes in the substance of higher modes while there would be no problem in the first mode. Displacement-based adaptive pushover (DAP) was similar to FAP; however, a displacement loading is used instead of force actions in DAP method. Generally, DAP structural demand estimation is more reliable than FAP. Both FAP and DAP might be regarded as rational methods because of their strong conceptual backgrounds and also considering effects of higher modes, interaction between modes, and variations in dynamic properties [28,30].

In 2009, Poursha et al. provided the consecutive modal pushover procedure (CMP) for estimating the seismic demands of structures [31]. A single-stage and few multi-stage pushover analyses were performed during CMP. In the single-stage pushover analysis, an inverted triangular load pattern (TLP) for medium-rise buildings and a uniform force distribution for high-rise buildings were used.

The multi-stage CMP is a consecutive non-linear static analysis using different mode load patterns until the roof reaches predetermined target displacement. In the multi-stage pushover analysis, finishing one step completely, the next step starts with the same initial structural state as the end of the previous stage. Although, this method presented proper results for higher levels, the outcome for lower levels were not accurate. Briefly, CMP underestimated the effects of the lower modes. This problem was solved by the authors employing a parallel traditional method (single-stage pushover analysis using inverted triangular or uniform load patterns). The responses of the higher levels were mostly obtained from the multi-stage CMP and the lower level responses were obtained from traditional methods [32]. In 2015, an extended CMP was developed by Poursha et al. to estimate the seismic demands of buildings under influence of two horizontal components of ground motions. The extended CMP was able to predict the seismic displacements at the flexible and stiff edges of the two-way asymmetric-plan buildings with sufficient accuracy [33].

In the current study, the modal shear-based pushover (MSP) procedure is developed to consider the higher mode effects. In this procedure a rational lateral load pattern is presented based on modal shear portion which makes it capable to estimate the seismic demand of tall buildings. In the following sections modal response analysis and some pushover-based methods are introduced, followed by the formulation of the MSP method.

2. Modal response analysis

The differential equation governing the response of a multi-degree

Table 1
Characteristics of the 3 and 9-story SAC buildings (Los Angeles).

No. of stories	*H* (m)	Periods		
		T1 (s)	*T2* (s)	*T3* (s)
3	11.88	1.01	0.33	0.17
9	37.17	2.27	0.85	0.49

Table 2
Characteristics of the 10, 15, 20 and 30-story buildings.

No. of stories	*H* (m)	Seismic mass of floors (kN/m)	Periods		
			T1 (s)	*T2* (s)	*T3* (s)
10	32	55.48	1.697	0.605	0.347
15	48	56.57	2.338	0.854	0.493
20	64	57.12	3.092	1.135	0.67
30	96	57.63	3.866	1.381	0.798

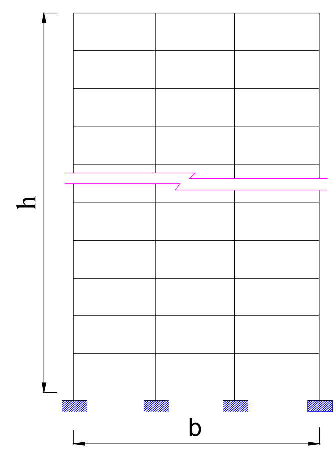

Fig. 1. Two-dimensional frames configuration.

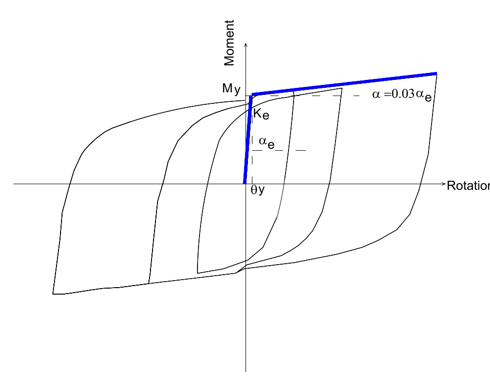

Fig. 2. Hinges generalized load-deformation curve.

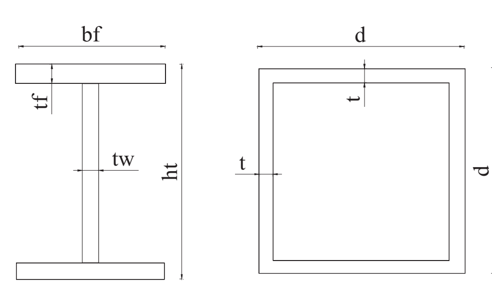

Fig. 3. The sections of beam and column elements.