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Effect of higher modes on the seismic response and design of moment-resisting RC frame structures

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ABSTRACT

Recently, extensive research has been conducted regarding higher-mode effects on the response of multi degree-of-freedom (MDOF) systems. The research has been focused mainly on structures with a lateral force resisting system consisting of slender walls, since these types of buildings are expected to be mostly affected by higher-mode phenomena according to structural dynamics, and simplified expressions have been proposed for slender-wall structures to account for higher-mode response in estimating shear forces. Current seismic design practice assumes the same reduction factor for all modes, even though there is strong evidence that inelasticity affects higher modes of vibration unequally. Additionally, simplified design methods are based only on the fundamental mode of vibration neglecting the effect of higher modes or considering them as elastic. In this paper, higher-mode contributions on the overall response of a nine-storey moment resisting frame (MRF), for which a domination of the first mode is expected, are investigated. The accuracy of a modified Modal Response Spectrum Analysis (mMRSA) method and other available methods is evaluated by comparing the results with the ones of the nonlinear response history analysis. Modal behaviour (reduction) factors are directly calculated for the first three modes and the validity of common assumptions is examined. The assessment of the methods is not restricted to deformations, but is extended to storey inertial forces and shears as well, which have attracted less interest from structural engineers, even though they are considered responsible for numerous structural and non-structural failures during major recent earthquakes and are critical for the design of several structures, such as precast buildings. The results suggest that the storey inertial forces and accelerations at all storeys and shear forces at higher storeys are significantly underestimated by methods neglecting or non-properly accounting for higher modes, even for first-mode dominated structures. The contribution of higher modes depends on the ground motion characteristics, the overstrength associated with each mode and the response quantity examined.

1. Introduction

The contribution of higher modes to the dynamic response of multi degree-of-freedom (MDOF) systems is an issue of addressed significance affecting the design of new structures and the assessment of existing ones. As a result of higher-mode vibrations, two main phenomena have challenged the interest of engineers during the last decades.

The first phenomenon, known as shear amplification, describes the amplification of shear demands due to higher modes and was firstly addressed by Blakeley et al. [1] for yielding slender walls. The amplification of the shear forces was found to increase with increasing fundamental period and ductility [2,3]. The shear amplification is expected to be more pronounced in slender walls, where the higher modes' effective modal mass is larger and also, well separated periods are observed compared to frames; therefore, it is more likely for slender shear walls to retain the second eigenperiod, T_2, in the acceleration-sensitive region of the response spectrum, affecting the base shear, while the first eigenperiod T_1 is located at the velocity- or even the displacement-sensitive region [4,5]. Several methods can be found in the literature to account for shear amplification [6–8] while an extensive review of the engineering studies regarding shear magnification in RC structural walls can be found in [9].

The second phenomenon, known as floor acceleration magnification, demonstrates the unexpectedly large earthquake-induced accelerations that have been recorded during seismic events or evaluated based on analytical models. During the Northridge, 1994, earthquake, maximum floor accelerations, more than four times the peak ground acceleration, were measured [10]. The floor acceleration magnification phenomenon is strongly related to the inertia forces, since the ratio of the storey inertia force to the storey mass is equal to the storey acceleration in a lumped-parameter

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approach of multi-storey structures; thus, an inaccurate evaluation of storey accelerations suggests an imprecise estimation of storey inertial forces. Several indications suggest that numerous failures or even collapse of buildings during past earthquakes were induced by large floor accelerations not expected from the design [11–13]. The accurate calculation of inertial forces is critical for the design of numerous structural components, as diaphragms and connections of precast or steel buildings [14–16], and non-structural components, as equipment [17], which is based on floor accelerations [18–20]. Furthermore, an as-possible-accurate estimation of lateral forces can improve the performance by making more uniform the distribution of maximum inter-storey drifts and enhance design economy [21,22].

Extensive recent research revealed that simplified methods for the calculation of the seismic loads, which are based on the fundamental mode and are adopted by seismic codes, fail to estimate accurately the inertial forces and the seismic floor accelerations [21,23–25]. Recently, Chao et al. [21] showed that significant dispersions can exist between storey inertial forces, which are calculated by the linear static analysis (LSA) (also termed ‘‘lateral force method’’ or ‘‘equivalent static analysis’’) of NEHRP 2003 and International Building Code 2006 provisions and nonlinear response history analysis (NLRHA) results, especially for the upper storeys. This inconsistency was also observed during pseudo-dynamic tests that were conducted with precast concrete buildings [26,27]. It was shown that the storey forces do not follow a decreasing tendency from the upper to the lower levels, as it would be expected by a first mode dominated response, even in the case of a fully regular and symmetric three-storey precast building [27].

In order to determine the maximum seismic demand for the design of new structures, modern seismic codes, including Eurocode 8 (EC8) [28] adopt multi-modal analysis procedures, such as the standard Modal Response Spectrum Analysis (MRSA) (also termed ‘‘linear dynamic’’ analysis) where the maximum base shear is given as a combination of the maximum modal responses. This method, even though it is widely accepted and used by contemporary codes and is well established in engineering practice, has, among others, two significant shortcomings in view of the previous discussion:

(1) A single value for the yield reduction factor R_y (also called behaviour factor, q_y) is considered for all significant modes of vibration.
(2) Design spectral values are calculated using the elastic periods without accounting for the critical change of stiffness during the development of inelasticity.

However, recent studies have shown that the ductility demand associated with higher modes might be significantly reduced [29,30]. For buildings with main lateral force resisting system comprised of structural walls, it was shown that the modal reduction factors decrease with increasing order of modes [23] and that the assumption of elastic behaviour for higher modes may lead to reasonable results [30]. However, limited available results on frame structures have shown that inelasticity can also affect higher modes. Applying a Multi-Mode Pushover procedure (MMP), Sasaki et al. [31] provided evidence that there is a possibility that the 2nd mode exceeds the elastic limit, while the 1st and 3rd modes remain elastic. In other words, it is possible that a higher mode turns nonlinear while lower modes remain linear, as was shown by Paret et al. [32] for a 17-storey steel frame building. Thus, the assumption that the reduction factors R_y decrease with increasing mode-order might be inaccurate in several cases. It is noted that, although local ductility is evidently related to the total deformation of the structure, under the assumption that modal analysis can be extended to nonlinear response member deformations are associated with the corresponding modal displacements and, thus, the notion of modal ductility can be established. On the other hand, the assumption of elastic higher-mode response might result in conservative predictions of storey shear forces [33]. Indicating the inconsistency of using the elastic modes for inelastic behaviour, Sullivan et al. [34] proposed a new modal superposition method that uses transitory inelastic modes.

Except of the standard MRSA method, several nonlinear static procedures (NSP) (or push-over analyses) have been proposed to evaluate the seismic performance of MDOF structures. EC8 [28] incorporates the N2 method, originally proposed by Fajfar and Fischinger [35]. However, the selection of a single lateral force distribution is believed to provide accurate results only for structures dominated by the first mode. To assess the contribution of higher modes of MDOF structures, several multi-mode pushover methods have been proposed in the literature [36–40]. Some of them imply an adaptive lateral load vector [41,42], while others attempt to capture the probabilistic nature of the seismic response and the continuous modification of the dynamic characteristics of MDOF systems at different intensity levels [43]. A detailed discussion on some of these methods can be found in [42]. Finally, several seismic codes and design standards, such as Eurocode 8 [28], ASCE/SEI 7-05 [44] and Tall Buildings Initiative [45], suggest, as an alternative to the common MRSA, LSA or NSPs methods, to conduct a number of NLRHA in order to properly account for higher mode effects. The proper selection and scaling of the seismic records to be used as base excitations remains an issue of research [46].

In the investigation presented herein, higher mode effects on a nine-storey RC plane frame structure are examined. The selected frame meets the provisions of Eurocode 8 [28] for the assessment of the inelastic response through a single-mode pushover procedure. For the estimation of higher-mode effects, the Uncoupled Modal Response History Analysis (UMRHA) method is applied. The method was originally developed as a precursor of the MPA method [36]. A modified Modal Response Spectrum Analysis (mMRSA) is also proposed, which, in contrast to the standard MRSA, uses inelastic response spectra without assuming a unique value of R_y for all modes. The idea of using inelastic spectra or empirical R_y–μ formulas for the calculation of the maximum modal displacements and accelerations was also proposed by Goel and Chopra [47] as a possible simplification of MPA. However, in mMRSA, storey deformations and internal forces are not extracted from the pushover database as in MPA, but are directly calculated from the modal responses as explained in the following section.

The effectiveness of these methods and other commonly used ones, as the standard MPA [36], the modified MPA [37], the N2 [35] and the extended-N2 [39], is assessed by comparison of the results for a set of earthquake records with the ones of NLRHA. It must be noted that there are other methods available in the literature which may also provide results of the same accuracy, as for example the Modified Modal Superposition method (MMS) proposed by Priestley and Amaris [29] and other similar ones that consider elastic response for higher modes. Those methods, however, are more oriented at design, while this study is more centered on evaluating the ductile response of higher modes.

The results of the analyses show that the inertial forces may be strongly affected by the higher modes of vibration even for a first-mode dominated frame structure. The suggested mMRSA procedure, and the other examined multimode pushover methods such as MPA, may provide an accurate estimation of these forces, while N2 leads to non-conservative results.

2. Considered methods of analysis

The results that are presented in the next section were obtained using several methods for the nonlinear analysis of structures that