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Investigation of efficiency of vector-valued intensity measures for displacement-sensitive tall buildings

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A R T I C L E I N F O

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A B S T R A C T

The design of tall buildings is different from that of ordinary buildings and performance-based earthquake engineering (PBEE) plays an important role in the design and assessment of tall buildings. Incremental dynamic analysis (IDA) is mainly the method used to analyze tall buildings in the framework of PBEE. Owing to the enormous amount of computation in IDA, seeking an efficient intensity measure (IM) is of vital importance. When an efficient IM is used, the number of seismic records and nonlinear analyses for IDA can be significantly reduced without affecting the accuracy, which is important in IDA especially for tall buildings where elasto-plastic time-history analysis requires more time. However, there have been only few studies on IMs for tall buildings. Moreover, although IMs have been extended from the scalar-valued type to the vector-valued type, there are no vector-valued IMs proposed for tall buildings. Thus, in order to provide a systematic investigation on IMs for a specific type of tall structures, this study investigated six vector-valued IMs as well as their scalar types for a displacement-sensitive tall building. The investigated IMs included five acceleration-based IMs with three considering nonlinearity development and two incorporating higher modes effect, as well as one velocity-typed IM. IDA was carried out for the structure under fifteen ground motions and the residual sum of squares (RSS) as well as R^2 values were calculated to compare the efficiency of the IMs. The results indicate that for a displacement-sensitive structure, the peak ground velocity (PGV) is the most efficient scalar-valued IM, while the $< S_a(T_1)$, PGV $>$ is the most efficient vector-valued IM. The vector-valued IMs are more efficient than corresponding scalar-valued IMs. The IMs considering nonlinearity are more efficient than the IMs incorporating higher modes and within a certain range the more refined the considered nonlinearity is, the more efficient the IM becomes.

1. Introduction

Tall buildings are becoming popular around the world because of the modernization of cities and limitation of space resources. The design of tall buildings is different from that of ordinary buildings. On one hand, there are some special structures in tall buildings such as strengthened story and transfer story that are not common in ordinary buildings. On the other hand, the nonlinear response of the overall structure and the structural components of the tall building under major earthquakes need to be considered emphatically when the structure is analyzed. Besides, professional and technical research by field experts is needed for some tall buildings since they are not covered by the current standards.

The performance-based seismic design, a valid assessment method that plays an important role in design and assessment of tall and super-tall buildings, has been gradually applied to actual tall building projects. As a significant method in performance-based earthquake engineering (PBEE), incremental dynamic analysis (IDA) has been investigated and used to analyze tall buildings by various scholars. Asgarian et al. [1], Mwafy [2], Lu et al. [3,4], Hariri-Ardebili et al. [5], and Lu et al. [6] analyzed different tall and super-tall structures by IDA.

Seeking an efficient intensity measure (IM) is of vital importance in IDA. As a specific word used in IDA, efficiency is the most important characteristic property of IM, which means little variability of the engineering demand parameter (EDP) under a given IM. When an efficient IM is used, the number of seismic records and nonlinear analyses for IDA can be greatly reduced without affecting the accuracy, which is significant in IDA, especially for tall buildings where elasto-plastic time history analysis takes more time. However, because of the enormous level of computation in IDA, there are few studies on IMs for tall buildings. Moreover, although IMs have been extended from the scalar-valued type to the vector-valued type, there are no vector-valued IMs proposed for tall buildings. Current IMs for tall buildings are generally based on the peak ground motion parameters or the spectral values of

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acceleration, velocity, and displacement response spectra. The IMs based on the spectral values of acceleration response spectrum are basically the parameters formed by the combination of the spectral values of the spectrum under different periods. Asgarian et al. [7] proposed the relation $S_a(T_n) = S_a(\tau_a, 5\%)^{1-\beta-\gamma} \cdot S_a(\tau_b, 5\%)^{\beta} \cdot S_a(\tau_c, 5\%)^{\gamma}$, where $\beta = \gamma = 1/3$, based on the acceleration spectrum values of the first three modes of a structure. Then, by combining the spectral values under multi-structural periods, Lu *et al.*[3] presented the relationship $\overline{S_a} = \sqrt[n]{\prod_{i=1}^{n} S_a(T_i)}$ to include the effect of the higher modes for tall buildings. Moreover, Bianchini et al. [8] suggested a multi-valued IM $S_{a,avg}(T_1, ..., T_n) = [S_a(K_l T^{(1)}) \times \cdots \times S_a(K_u T^{(1)})]^{1/10}$ for tall buildings to incorporate the higher modes effect and nonlinearity development simultaneously. In the above expression, K_l is used for the higher modes effect and K_u is used for the nonlinearity development. In particular, Adeli et al. [9] used the area of the acceleration response spectrum in the interval $[1.2T_m, 1.5T_1]$ as an IM to consider the impact of nonlinearity and higher modes simultaneously.

The IMs mentioned above treat different modes equally. However, this is unreasonable since the contribution of different modes is obviously different. Hence, in order to consider different effects of different modes, Lin *et al.*[10] proposed S_{N2} for structures with the first structural period $T_1 > 1.5$ s, which is expressed as $S_{N2} = S_a(T_1)^{0.75} \cdot S_a(T_2)^{0.25}$. This IM is based on the spectral values of the acceleration response spectrum under the first two periods of a structure. Su et al. [11] proposed S_{12} and S_{123} to consider the spectral values of the first two and three periods. In the above expression, S_{12} is expressed as $S_{12} = [S_a(T_1, \xi)]^{\alpha} \cdot [S_a(T_2, \xi)]^{\beta}$, where $\alpha = m_1/(m_1 + m_2)$, $\beta = m_2/(m_1 + m_2)$, and m_i is the modal mass participating coefficient of the i^{th} mode, S_{123} is expressed as $S_{123} = [S_a(T_1, \xi)]^{\alpha} \cdot [S_a(T_2, \xi)]^{\beta} \cdot [S_a(T_2, \xi)]^{\gamma}$, where $\alpha = m_1/(m_1 + m_2 + m_3)$, $\beta = m_2/(m_1 + m_2 + m_3)$, $\gamma = m_3/(m_1 + m_2 + m_3)$, and m_i is the modal mass participating coefficient of the i^{th} mode.

Based on the spectral values of velocity and displacement spectra as well as the peak ground motion parameters, Lu et al. [12] investigated the efficiency of peak ground acceleration (PGA), peak ground velocity (PGV), $S_a(T_1)$, and $S_d(T_1)$ for tall buildings and proved that PGV was preferable for seismic design and elasto-plastic analysis of super-tall buildings. Hariri-Ardebili et al. [5] compared the efficiencies of PGV, PGD, CAV, $S_a(T_1)$, S_{12}, and S_{123} and indicated that PGV and S_{123} were more suitable for the investigated tall concrete tower.

As seen from the literature review above, there are few studies on the scalar-valued IMs and none on the vector-valued IMs for tall buildings. Moreover, for different tall buildings, the most efficient IM may be different. Therefore, this paper proposes to divide tall buildings into different types in order to study the efficiency of IMs and attempts to provide a systematic study on IMs for a specific type of tall structures, namely the displacement-sensitive tall structure.

2. Engineering demand parameters and intensity measures

The engineering demand parameter (EDP) is used to characterize the dynamic response of a structure under earthquakes. It should be easily derived from the results of nonlinear analysis and should desirably demonstrate the dynamic performance of the structure under seismic actions. The choice of the EDP depends on the purpose of the research and the characteristics of the structure. Basically, the commonly used EDP includes the maximum base shear, the maximum inter-story drift ratio, and the top displacement. The maximum inter-story drift ratio ($\theta_{\max}$) is generally considered the most frequently used EDP since it can reflect the desirable damage of the structure [7]. In this paper, $\theta_{\max}$ is chosen as the EDP based on the structural property and the research purpose.

The intensity measure (IM) is a parameter used to indicate the ground motion intensity. In IDA, the ground motions of different intensities are obtained by adjusting the IM proportionally and the results of IDA should be expressed by IM and EDP. Choosing different IMs leads to different discretization of IDA curves. For many years, researchers have attempted to identify the IMs that are efficient enough to reduce the variability of different ground motion records. The IMs used for this