Engineering Structures 165 (2018) 302–314

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Modified spectrum-based pushover analysis for estimating seismic demand of dual wall-frame systems

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ARTICLE INFO

Keywords:
Dual wall-frame system
Spectrum-based pushover analysis
Seismic demand
High mode effect
Nonlinear analysis
Tall building

ABSTRACT

Although many advanced pushover-based models have been developed for the fast prediction of seismic demand of tall buildings, most of these models are only focused on the analysis of moment-resisting frame structures. The seismic behaviour of dual wall-frame structures is very different from that of a moment-resisting frame structure, as structural walls and frames have totally different deflected shapes under the action of lateral loading, thus resulting in a strong structural interaction between the two load-resisting systems. There are few pushover-based models, in which the different structural responses between structural walls and frame structures are included. In this paper, modification of the spectrum-based pushover analysis (SPA) is presented to consider the structural interaction between shear walls and frames and the different damage modes of a dual wall-frame structure. In the modified spectrum-based pushover analysis (MSPA) method, the force vectors applied to the structure and formulations for determining the total roof displacement are changed to take the wall-frame interaction into account. The applicability and accuracy of MSPA in predicting the seismic demand of dual wall-frame structures are investigated through a case study of four 25-storey reinforced concrete wall-frame structures subjected to different levels of the input ground motions. Comparison of the results from nonlinear response time history analysis (NLRHA), several advanced pushover-based models and the proposed MSPA method has been made. It is seen that only MSPA can predict the distribution of the seismic demand along the height of buildings well, and the seismic demand from MSPA shows very good agreement with that from NLRHA.

1. Introduction

The 2008 Great Sichuan earthquake in China devastated an area over 440,442 km^2 in Sichuan province, China. Numerous buildings and structures were turned into a mass of debris inflicting a high death toll of over 69,100, with some 374,000 people injured and about 4.8 million left homeless in the province. Many old non-seismically designed and newly seismically designed reinforced concrete dual wall-frame structures suffered unexpected severe damage. The unexpected structural damage of reinforced concrete dual systems has also been reported in destructive earthquake events, including the 1971 San Fernando Earthquake, the 1985 Mexico City earthquake, the 1999 Taiwan Chi-Chi and Turkey Kocaeli earthquakes, and the 2010 Haiti and Chile earthquakes. Although in recent years many pushover-based methods of analysis have been developed for predicting the seismic demand of buildings [1–14], most of them are only used for the analysis of frame structures. Hence, there is still an urgent need for developing efficient, accurate and fast methods of evaluating the seismic demand of tall buildings with different structural forms.

Among these advanced pushover-based models, modal pushover analysis (MPA) method [1] and modified modal pushover analysis (MMPA) [4] are two of the most popularly used models. With the assumption that vibration modes are still independent in the nonlinear stage, MPA and MMPA methods predict the response demand of different modes separately and combine the demands by the modal combination rule. The consecutive modal pushover (CMP) analysis [6] and modified consecutive modal pushover (MCMP) analysis [11] are the methods that consider the interaction of vibration modes, where a few sets of forces with mode shape distribution are applied to the building consecutively. Recently, the spectrum-based pushover analysis (SPA) [14], a promising method of analysis for the fast prediction of seismic demand of tall buildings, was developed, where the dynamic coupling of vibration modes is simplified, and the target roof displacement for the pushover procedures is obtained from the design spectrum. However, it is noted that all these advanced pushover-based methods are primarily focused on the analysis of frame structures.

The dual wall-frame structure is the combination of a structural wall system and a rigid frame system and is considered as one of the most

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https://doi.org/10.1016/j.engstruct.2018.03.043
Received 27 October 2017; Received in revised form 15 March 2018; Accepted 15 March 2018

popular structural forms for medium-rise and high-rise buildings. The seismic behaviour of the dual system is very different from that of a frame structure. This is because the overall deflected shapes of a shear wall structure and a rigid frame structure have generally a flexural configuration and a shear configuration, respectively, subjected separately to horizontal loading, thus resulting in the strong structural interaction between the wall and frame systems. In general, when subjected to seismic actions, the dual wall-frame structure has a flexural profile in the lower part and a shear profile in the upper part due to the effect of the wall-frame interaction [15,16], indicating that the wall and frame systems play a more important role in seismic resistance in lower storeys and upper storeys of the building, respectively. Although the advanced pushover-based methods of analysis can predict the seismic demand of frame structures well, the applicability and accuracy of these methods in predicting the seismic demand of dual wall-frame structures are not guaranteed and questionable. However, few studies have been conducted to verify the applicability of these pushover-based methods in estimating the seismic demand of the dual wall-frame systems. In addition, few pushover-based models have been developed for quick prediction of seismic demand of these dual structures.

This paper presents a modified spectrum-based pushover method of analysis (MSPA) for quick evaluation of seismic demand of dual wall-frame structural systems. The SPA method is modified where the forces vectors are changed to be used for pushover analysis and formulations for determining the roof displacement to take into account the wall-frame interaction and special damage modes of the wall-frame structure. The applicability and accuracy of the proposed MSPA in predicting the seismic demand of dual wall-frame structures are investigated through a case study of four 25-storey reinforced concrete wall-frame structures subjected to different levels of input ground motion. It is shown from the comparison of the results from nonlinear response time history analysis (NLRHA), the advanced pushover-based models including MPA and CMP methods, and the proposed MSPA that only MSPA can predict the trend of the distribution of seismic demand along the height of buildings well, and the predicted seismic demand from MSPA shows very good agreement with that from NLRHA.

2. Equation of motion for a nonlinear system

The elastic response of an N-degree of freedom system under the ground motion is governed by the following equation

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{k}\mathbf{u} = -\mathbf{m}\mathbf{i}\ddot{u}_g(t) \tag{1}$$

where $\mathbf{u}$ is the floor displacements vector, $\mathbf{m}$, $\mathbf{c}$ and $\mathbf{k}$ are the mass, classical damping and stiffness vector of the system respectively; $\mathbf{i}$ is the unit vector. The right-hand side of Eq. (1) represents the effective earthquake force and can be written as

$$\mathbf{p}_{eff}(t) = -\mathbf{m}\mathbf{i}\ddot{u}_g(t) = -\mathbf{s}\ddot{u}_g(t) \tag{2}$$

where $\mathbf{s}$ represents the spatial distribution of the effective forces over the height of the building, and can be expanded as a summation of the modal inertia force distributions s_n as follows,

$$\mathbf{s} = \sum_{n=1}^{N} \mathbf{s}_n = \sum_{n=1}^{N} \Gamma_n \mathbf{m}\phi_n \tag{3}$$

where ϕ_n is the nth natural vibration mode of the structure, and

$$\Gamma_n = \frac{L_n}{M_n}, \quad L_n = \phi_n^T \mathbf{m}\mathbf{i}, \quad M_n = \phi_n^T \mathbf{m}\phi_n \tag{4}$$

By the summation of the model response, the displacement of an N-degree of freedom system can be expressed as

$$\mathbf{u}(t) = \sum_{n=1}^{N} \phi_n q_n(t) \tag{5}$$

where the modal co-ordinate $q_n(t)$ is governed by

$$\ddot{q}_n + 2\xi_n\omega_n\dot{q}_n + \omega_n^2 q_n = -\Gamma_n\ddot{u}_g(t) \tag{6}$$

The solution of Eq. (6) is given by

$$q_n(t) = \Gamma_n D_n(t) \tag{7}$$

where $D_n(t)$ is governed by the equation of motion for a single-degree-of-freedom (SDOF) system subjected to $\ddot{u}_g(t)$,

$$\ddot{D}_n + 2\xi_n\omega_n\dot{D}_n + \omega_n^2 D_n = -\ddot{u}_g(t) \tag{8}$$

The floor displacement can then be represented as

$$\mathbf{u}(t) = \sum_{n=1}^{N} \mathbf{u}_n(t) = \sum_{n=1}^{N} \Gamma_n\phi_n D_n(t) \tag{9}$$

When the structure yields, the unloading and reloading curves will be different from the initial loading branch. Hence, the lateral force is no longer independent of the loading history and should be expressed as:

$$F_s = F_s(\mathbf{u},t) \tag{10}$$

Therefore, the governing equation of motion for the nonlinear system is expressed as

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{f}_s(\mathbf{u},sign\dot{\mathbf{u}}) = -\mathbf{m}\mathbf{i}\ddot{u}_g(t) \tag{11}$$

3. Modified spectrum-based pushover analysis (MSPA)

It is seen from Eq. (11) that the modes of vibration are coupled after yielding of a structure. The complex coupling behaviour of modes should be considered when determining the nonlinear seismic demand of structures. To consider the coupling effect of modes of vibration while keeping the efficiency of the pushover analysis method, a simplification of the mode coupling is adopted in the SPA method [14], where the modes of vibration are directly connected with the structural state (internal stress, strain and displacement) when vibration of the mode is initiated. The simplification is that when the ith mode of vibration starts, the roof displacements of all previous modes (the $(i-1)$ th, $(i-2)$th, …, and 1 st mode) of vibration have already reached the target values, and the structural conditions, such as roof displacement, storey drift, internal stress and strain of the ith mode keep unchanged after the roof displacement of ith mode reaches the target value. The consecutive pushover technique is used to reproduce structural states of building structures, where when one pushover procedure is completed; the next pushover procedure will be started with the initial structural state the same as that in end of the immediate past pushover procedure. Forces with elastic mode shape distribution ($m\phi_i$), where ϕ_i is normalised so that the value at the roof ϕ_{ri} is 1, are used to conduct the pushover analysis. The order of the consecutive pushover procedure should follow the order of modes, which is from the 1st mode to higher modes. The force distributions for the first three pushover analysis stages in SPA for a 20-storey SAC frame structure in the previous study are presented in Fig. 1(a).

The location of the plastic hinges initiated in the first pushover stage for the frame structure is shown in Fig. 2(a), where the forces with a first mode shape distribution, $m\phi_1$, were used. It is seen that the plastic hinges caused by first-mode shape distributed forces are mainly concentrated in the lower part of the frame structure. With the increase in the roof displacement, the plastic deformation at the bottom will become much larger than other parts. After experiencing larger plastic deformation, the frame members at the bottom should take smaller