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An approach to equivalent damping ratio of vertically mixed structures based on response error minimization

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ABSTRACT

Damping property of vertically mixed structure is hard to identify, especially in the design stage since it is strongly rely on the configuration of the two component structural parts. In this paper, a decoupling approximation for dynamic response analysis of the vertically mixed structure is proposed. The optimal equivalent uniform damping ratio can be evaluated in a sense of response error minimization. It is calculated by using the superposition response spectrum method which takes the full frequency content of the ground motion into consideration rather than the harmonic excitation at a specified frequency only. The equivalent uniform damping ratios presented here are then validated by comparison with full time history analysis. Over the most part of the (R_{ω}–R_m) parametrical plane, the response error is relatively small for the each component structural parts. And then, the proposed damping ratios are tested in actual MDOF concrete/steel irregular structures. It is shown that the proposed procedure is proved to be feasible in use for practical design.

1. Introduction

In recent years, more and more complicated structural systems have been emerged in the construction of high-rise buildings in order to meet the demand for varied functions and novel configuration. Vertically mixed steel–concrete structure is the one among them and can be occasionally found in practical engineering application. It usually consists of two parts, a lower part made of concrete and an upper part made of steel. Its lateral stiffness varies vertically to satisfy the needs of structural deformation. Several applications of such structural configurations can be found in China, as shown in Fig. 1 [1] and Fig. 2 [2]. The response behavior of the vertically mixed structure can be very irregular and complex when it is subjected to dynamic loads. This irregularity may arise from damping property which is hard to identify due to different energy dissipation mechanisms of the materials distributed over the height of the structure.

Current seismic design codes, either Chinese Code for Seismic Design of Buildings (CCSDB, GB50011-2010) [3] or EC8 [4], do not have specifically provisions for the seismic analysis of such kind of structures. An overview of the existing analysis methods and the pertinent code provisions was presented by Villaverde [5]. In general, these methods can be grouped into two categories: one is the decoupled approach. In this way, two subsystems of the structure are considered separately, and each part is modeled with its own damping ratio, thus damping irregularity is avoided, as shown in Fig. 3(b). This method is especially useful for the equipment-structure systems in which the mass of the equipment is quite smaller than the whole structure [6]. However, when the masses of different parts are comparable, as the ones mentioned above, significant inaccuracies may arise from the interaction between different parts being neglected [7]. In the second method which is usually mentioned as a coupled approach, the structure is modeled as a whole, as shown in Fig. 3(a). The coupled approach avoids the decoupling error but has more analysis difficulties in the formulation of the irregular damping matrix. Consequently, a classical modal analysis, which would be very convenient for practical design, does not yield a diagonal normalized damping matrix, and thus complex eigenmodes are needed in order to avoid a full time history analysis. In practice, many engineers end up with using an overall conservative uniform damping ratio equal to 2% for security reasons, thus obviously underestimating the consuming energy performance of the concrete part [8]. However, in the initial stage of structural designing, especially with a commercial software, a uniform damping ratio as a fundamental input parameter is required to be determined. Therefore, the concept of equivalent uniform damping ratio is needed for design of this irregular structure.

The equivalent uniform damping ratio method is a simple and approximate procedure for irregularly damped case, thus permitting code compatible design. One of the most conventional ways to determine the equivalent uniform damping ratio of the irregularity structures is based on energy conservation. In this method,

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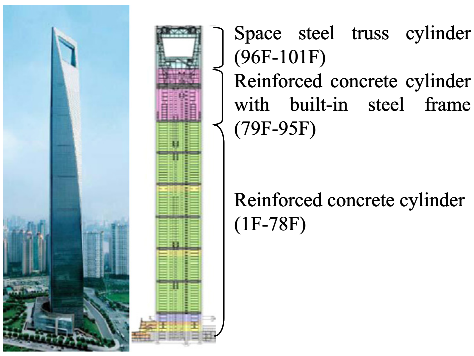

Fig. 1. Shanghai World Financial Center.

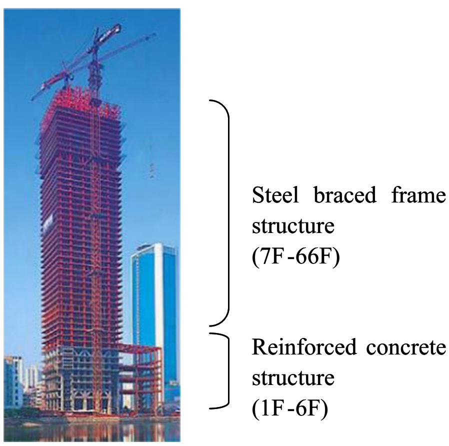

Fig. 2. Wuhan International Securities Building.

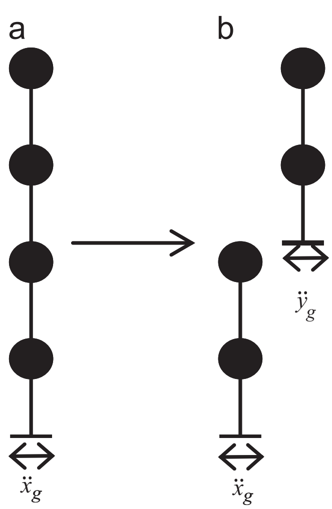

Fig. 3. Coupled (a) and decoupled (b) analysis procedure.

modal equations are assumed to be uncoupled, and each modal damping is estimated either by quantifying the dissipated energy with different parts [9] or modal strain energy method [10], which specified the energy as the elastic strain energy. This expression has clear physical meanings and a simple form. Therefore, it has been widely used, such as Guide Specifications for Seismic Isolation Design in USA [11] and Manual for Menshin Design of Highway Bridges in Japan [12], to calculate the modal damping ratio of isolated structures. However, this method, which utilizes the undamped mode shapes for non-classical damping, is also an approximate procedure, and could significantly overestimate damping ratios for certain systems [13].

In the field of complex eigenvalues, Foss [14] extended classical modal analysis to a process of complex modal analysis in the state space to treat non-classically damped system. In a first attempt to combine the complex eigenvalues and an error estimation procedure, Papageorgiou and Gantes [15] proposed the equivalent modal damping ratio for irregularly damped structures to real valued analyses. A similar method was used to evaluate the equivalent damping ratio of a structure with supplemental damping devices by Lee et al. [16]. Although the exact solution can be computed by the complex method, this approach is seldom handled in an analysis and design process making use of commercial software by engineers, since it is not supported from physical point of view in the real world. In an alternative approach, Papagiannopoulos and Beskos [17] determined the modal damping ratios of irregularly damped structures with the aid of the frequency domain modulus of the transfer function and the resonant frequencies as well as the modal participation factors and mode shapes of the undamped structure. This proposed approximate identification method is assessed their efficacy in steel plane and spatial frames under seismic excitation.

In the practical engineering, many engineers seem to focus on the dynamic response of the structure under earthquake action. A trial and error procedure to extract a uniform damping ratio for a specific MODF structure, which the lower degrees of freedom were made of concrete and the upper ones were made of steel, is proposed by Huang et al. [18]. Then, they appropriately represented the entire structure with an equivalent SDOF–SDOF oscillator, using the first mode characteristics of each part, and proceeded with an analytical estimation of the modal damping ratios by assuming that the normalized damping matrix is diagonal. An expansion in their work is introduced by Papageorgiou and Gantes [19], where an equivalent damping ratio is derived by means of a semi-empirical error minimization procedure for handling the damping irregularity of such structure under resonance ground motion. The equivalent damping ratios are tested on seismic records with satisfactory results regarding the error in the response estimation. It has to be noticed that the equivalent damping ratio is derived by harmonic in resonance, which ignore the full frequency content of the ground motion.

The essence of the equivalent uniform damping ratio is to simplify the non-classical damping to the classical one. The method of decoupling approximation has been investigated by many authors and several indices are developed to quantify the extent of modal coupling in non-classically damped systems. The studies by Clough and Mojtahedi [20], Shahruz and Ma [21], and Veletsos and Ventura [22] showed that the decoupling approximation, which neglects the off-diagonal elements of the modal damping matrix, was the most efficient procedure to deal with non-proportional damping problem. Cronin [23] proved that the normalized damping matrix was diagonally dominant, and decoupled the system by neglecting the off-diagonal elements indeed minimize the error bound. Park et al. [24] and Morzfeld et al. [25] used the method of Laplace transform to derive the coupling indices that can be quantified the extent of non-classical damping systems. Based on this, the tight error bounds of decoupling approximation are proposed by Hwang and Ma [26] and Gui and Huang [27].

In this work, based on the Rayleigh damping model, a decoupling approximation for dynamic response analysis of the vertically mixed structure is proposed. The optimal equivalent uniform damping ratio can be evaluated in a sense of response error minimization. It is calculated by using the superposition response spectrum method which takes the full frequency content of the ground motion into consideration rather than the harmonic excitation at a specified frequency only. First, the irregular structure is appropriately substituted by representative 2-DOF oscillator model, where each of the two parts is modeled as one degree-of-freedom with the dynamic