Structural Engineering and Mechanics, *Vol. 50, No. 3 (2014) 383-401*
DOI: http://dx.doi.org/10.12989/sem.2014.50.3.383

Equivalent modal damping ratios for non-classically damped hybrid steel concrete buildings with transitional storey

Abbas Sivandi-Pour*, Mohsen Gerami and Daryush Khodayarnezhad

Faculty of Civil Engineering, Semnan University, Semnan, Iran

(Received August 27, 2012, Revised January 27, 2014, Accepted March 9, 2014)

Abstract. Over the past years, hybrid building systems, consisting of reinforced concrete frames in bottom and steel frames in top are used as a cost-effective alternative to traditional structural steel or reinforced concrete constructions. Dynamic analysis of hybrid structures is usually a complex procedure due to various dynamic characteristics of each part, i.e. stiffness, mass and especially damping. In hybrid structures, one or more transitional stories with composite sections are used for better transition of lateral and gravity forces. The effect of transitional storey has been considered in no one of the studies in the field of hybrid structures damping. In this study, a method has been proposed to determining the equivalent modal damping ratios for hybrid steel-concrete buildings with transitional storey. In the proposed method, hybrid buildings are considered to have three structural systems, reinforced concrete, composite steel and concrete (transitional storey) and steel system. In this method, hybrid buildings are substituted appropriately with 3-DOF system.

Keywords: hybrid buildings; damping ratio; transitional storey; steel-concrete; non-classical damping; nonlinear analysis; main modes

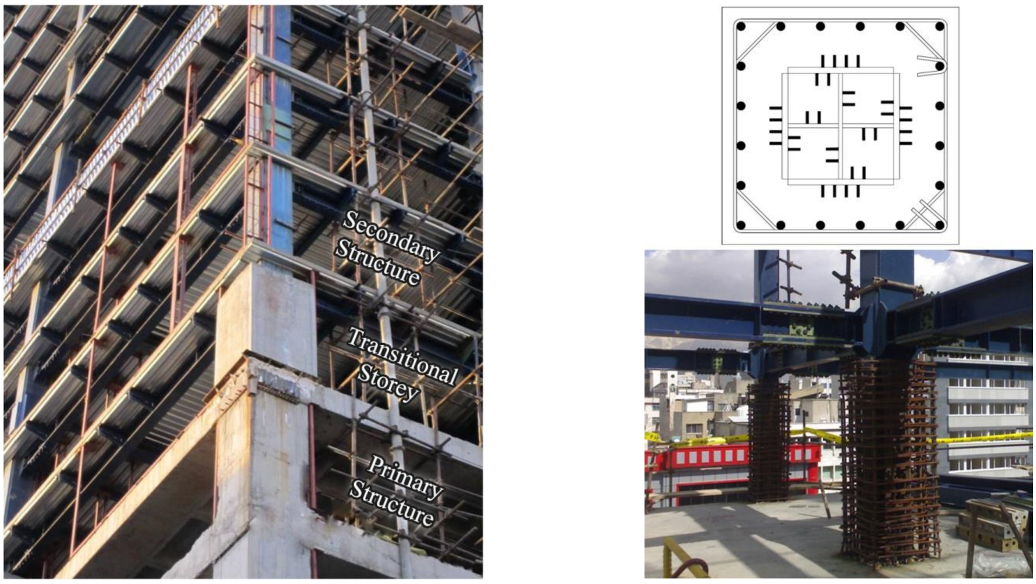
1. Introduction

Steel-concrete hybrid systems are used in buildings, in which a steel structure has been placed on a concrete structure to make a lighter structure and have a faster construction. In such irregular buildings, the lower reinforced concrete structure and the upper steel structure are called primary and secondary structures, respectively (Papageorgiou and Gantes 2005, Taranath 2011). In the hybrid structures, one or more transitional stories are used for better transition of lateral and gravity forces. In transitional storey, composite columns can also be constructed by encasement steel sections in concrete (Viest *et al.* 1997). A hybrid building with a transitional storey is shown in Fig. 1.

To analyze the behavior of the transitional storey in hybrid buildings, the behavior of steel-concrete composite columns must be assessed. One of the early methods to review the interaction between steel and concrete in composite sections is introduced by Basu and Sommerville (1996). The introduced method was later complemented, considering the effects of biaxial bending by experimental and analytical studies (Virdi and Dowling 1973, Johnson 2004). In a research done by Liu *et al*. (2012), a method was presented for the second-order analysis of these sections.

*Corresponding author, Ph.D. Candidate, E-mail: abbas.sivandi@gmail.com

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)



(a) (b)

Fig. 1 (a) Concrete-steel hybrid building (b) Details of transitional storey

Dynamic response of these structures has some complications. One of the reasons is the different stiffness of the two parts of structure and another reason is non-uniform distribution of materials and their different features such as damping in main modes of vibration. Damping is the dissipation of energy from a vibrating structure that is one of the effective factors in determining dynamic response of a structure (Fang *et al.* 1999, Hajjar 2002, Li *et al.* 2002). Specific ways in which energy is dissipated in vibration are dependent upon the physical mechanisms active in the structure. Availability of different damping factors causes a higher degree of complication for evaluating seismic responses of hybrid systems. On the one hand, the available design regulations do not present analytic methods for determining structural systems damping and on the other hand, damping matrix of these structures is non-classical. Also, the nonlinear software is not able to analyze these structures precisely. For dynamic analysis of these structures by using the available software, an equivalent modal damping ratio must be generalized to the whole structure. One general method for determining the damping of these structures is such that two structures are modeled as two separate systems, each of them considered with its damping ratio, and the interaction between the two systems is ignored, so that the damping ratios of primary and secondary structures were proposed 5% and 2%, respectively (Papageorgiou and Gantes 2005, Johnson 2004, Zona *et al.* 2008). This method introduced many errors and is very different from the real behavior of the structure. In the field of determining equivalent damping, Lee *et al*. (2004) performed some studies by direct solution and without using time history analysis by substituting Multi Degrees of Freedom (MDOF) structure by adding dampers to Single Degree of Freedom (SDOF) structure. In the field of complex eigen-vectors, Villaverde (2008) presented one method for using complex modes of an irregular building by maximum response. In this method, motion equations are reviewed in the state-space and their modal specifications are evaluated in spectral analysis method. Kim *et al*. (1999) presented a solution method to solve the eigenvalue problem raised in the dynamic analysis of non-classically damped structural systems. This method was obtained by applying the modified Newton-Raphson technique and the orthonormal condition of the eigenvectors. Xu (2004) presented a general formulation for computing rigorous explicit damping matrices for multiply connected, non-classically damped, coupled systems. Papagiannopoulos and Beskos (2006) investigated on the simple modal damping identification model. This model works in the frequency domain and provides time-invariant modal damping ratios of building structures under seismic excitations in terms of modal participation factors and the roof-to-basement transfer function. The performance of the model was assessed through a small, yet indicative, number of numerical examples involving steel plane and space frames under seismic excitations and on the basis of a number of criteria an ideal identification model should satisfy. The proposed model, in spite of its simplicity, gives very good results for low-amplitude seismic excitations resulting in linear elastic structural behavior (with damping) even for cases of closely spaced modes, local modes, and very small or large amounts of damping. A simple modal damping identification model was developed by Papagiannopoulos and Beskos (2009) for non-classically damped linear buildings subjected to earthquakes. The assumption is made that the modulus of the transfer function of non-classically damped structure matches the one of the classically damped structure in a discrete manner, i.e., at the resonant frequencies of that function modulus.

Huang *et al*. (1996) reviewed a series of MDOF irregular structures in a different method in which the reinforced concrete part had a lower degrees of freedom and metal part had higher degrees of freedom. In the method presented by these researchers, in the first stage, regular damping ratio of the whole building must have been obtained by trial and error method, and then the whole building was modeled by a 2-DOF system and modal damping ratio was calculated by predictive approximate method with the assumption that the normalized damping matrix is diametric. Papageorgiou and Gantes (2010) proposed equivalent modal damping ratio in their research for steel-concrete hybrid structures. The performed assumptions by these researchers were the same as the Huang *et al*. method (1996), being even more accurate. In their method, the system response was defined according to the features of the two parts by special frequency ratio and the ratio of the secondary to primary structure weight. Papageorgiou and Gantes (2010) proposed improved decoupling criteria for the seismic analysis of inelastic primary-secondary systems. In their method, each part is modeled as a 1-DOF system, and the maximum responses of coupled and decoupled inelastic dynamic analyses are compared over a wide range of dynamic characteristics and strength levels of the two parts. They presented the results in the form of error levels between the two alternative analysis procedures. Papageorgiou and Gantes (2011), proposed a methodology for dynamic analysis of hybrid buildings that makes use of semi- empirically obtained equivalent uniform damping ratios, and its efficacy was tested in actual structures. In their method, equivalent damping ratios that appropriately represent the dynamic response corresponding to the actual damping distribution were extracted through an error minimization procedure for a wide range of dynamic characteristics of the 2-DOF structure. In their research, the effect of transitional storey has not been considered in steel and concrete hybrid structures. As a matter of fact, the effect of transitional storey has been considered in none of the studies in the field of reviewing hybrid structures damping, so far. Since there is transitional storey(s) in design and construction of many hybrid buildings, using recent numerical methods causes the association of the performed analysis results with errors in comparison with their real behavior. In the proposed method in this study, the existence of transitional storey(s) has also been considered for calculation of equivalent modal damping ratios for non-classically damped hybrid steel-concrete buildings. In the proposed method, hybrid buildings are considered to have three structural systems

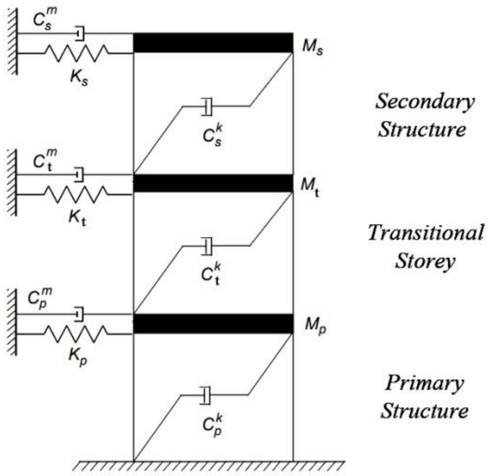


Fig. 2 Equivalent 3-DOF structure

of reinforced concrete, composite steel and concrete (transitional storey) and steel system. Transitional storey(s) has also been modeled by another SDOF system. The modal damping ratios proposed in this study can be used for the analyses and designing of structures in available commercial and research software such as SAP2000 and Opensees. Using the proposed methods and obtained graphs for determining modal damping ratios in dynamic analysis and nonlinear analysis of hybrid buildings has more care in comparison with the methods presented so far and the obtained response is closer to the structure's real behavior.

2. Hybrid structures modeling with transitional storey

There are two general methods for dynamic analyzing of concrete and steel hybrid structures with non-classical damping. The first method is the direct solution which includes structural dynamic procedures (Clough and Penzien 1993, Chopra 1995) and integration (Adhikari and Wagner 2004, Cortes 2009). Using direct method requires the calculation of stiffness, mass and damping matrices. The calculation of stiffness and damping matrices in direct method is complicated and becomes even more complicated as the degrees of freedom of the structure increase. Hence, using direct method is very time-consuming and hard and it is also impossible for the structures with higher degrees of freedom. The second method is devoting an equivalent damping to the whole structure and using the available software.

In the method proposed in this study, concrete, steel and transitional stories are appropriately substituted with 3-DOF structure as presented in Fig. 2 in order to form a hybrid structure.

In the next step, eigenvalues of each primary, transitional and secondary structure are obtained. Eigenvalues of each part include the first mode related frequency values (ω_i^1), mass (M_i^1) and modal stiffness (K_i^1). i can be related either to the primary structure, secondary structure or transitional stories. In the numerical method investigated in this study, p indicates the primary structure (concrete part), s presents the secondary structure (steel part) and t presents the transitional stories.

3. The proposed method for determining modal damping

The procedure of this investigation is based on the elastic analysis. The proposed method is restricted to the case that the structure remains elastic, thus the stiffness matrices employed here are the ones computed by the elastic properties of the structure. Cases of elastoplastic deformations and added damping devices escape the scope of this work. The main MDOF structure is assumed to have separate Rayleigh damping at each section. This is to say that damping ratio is proportional to stiffness and mass in each degree of freedom. So, each part of the equivalent 3 degrees of freedom has two types of damping C_i^k and C_i^m (damping proportional to stiffness and mass). Mass **M** and stiffness **K** matrices are calculated for each of the three parts of primary structure, transitional stories and secondary structure. Each of them shows the matrix forming the related part of the overall structure. A Matlab code was developed in order to calculate the equivalent modal damping ratios and to depict the graphs.

The structure's overall stiffness matrix is comprised of the stiffness of primary structure, transitional storey and secondary structure. Stiffness matrix of hybrid structure is obtained from the Eq. (1).

$$K = K^p + K^t + K^s = \begin{bmatrix} k_t + k_p & -k_t & 0 \\ -k_t & k_t + k_s & -k_s \\ 0 & -k_s & k_s \end{bmatrix} \tag{1}$$

The overall mass matrix of structure is obtained from mass matrix of each one of the three parts forming the structure is calculated from the Eq. (2).

$$M = M^p + M^t + M^s = \begin{bmatrix} m_p & 0 & 0 \\ 0 & m_t & 0 \\ 0 & 0 & m_s \end{bmatrix} \tag{2}$$

Modal frequencies of ω_1, ω_2 and ω_3 are obtained by classic analysis method for 3-DOF structure (Papageorgiou and Gantes 2010, Chopra 1995).

Primary structure's damping matrix is calculated from Eq. (3-1).

$$C^p = a_{0,p} M^p + a_{1,p} K^p \tag{3-1}$$

$$a_{0,p} = \frac{2 \times \xi_p \times \omega_1 \times \omega_3}{\omega_1 + \omega_3} \tag{3-2}$$

$$a_{1,p} = \frac{2 \times \xi_p}{\omega_1 + \omega_3} \tag{3-3}$$

Transitional storey's damping matrix is obtained from Eq. (4-1).

$$C^t = a_{0,t} M^t + a_{1,t} K^t + a_{2,t} K^t {m^t}^{-1} K^t \tag{4-1}$$

$$a_{0,t} = \frac{2 \times \xi_t \times \omega_1 \times \omega_2 \times \omega_3 \times (\omega_1 + \omega_2 + \omega_3)}{(\omega_1 + \omega_2) \times (\omega_1 + \omega_3) \times (\omega_2 + \omega_3)} \tag{4-2}$$

$$a_{1,t} = \frac{2 \times \xi_t \times \left(\omega_1^2 + \omega_1 \times \omega_2 + \omega_1 \times \omega_3 + \omega_2^2 + \omega_2 \times \omega_3 + \omega_3^2\right)}{(\omega_1 + \omega_2) \times (\omega_1 + \omega_3) \times (\omega_2 + \omega_3)} \tag{4-3}$$

$$a_{2,t} = -\frac{2\xi_t}{(\omega_1+\omega_2)\times(\omega_1+\omega_3)\times(\omega_2+\omega_3)} \tag{4-4}$$

Steel secondary structure's damping matrix is obtained from Eq. (5-1).

$$C^s = a_{0,s}M^s + a_{1,s}K^s \tag{5-1}$$

$$a_{0,s} = \frac{2\times\xi_s\times\omega_1\times\omega_3}{\omega_1+\omega_3} \tag{5-2}$$

$$a_{1,s} = \frac{2\times\xi_s}{\omega_1+\omega_3} \tag{5-3}$$

where, ξ presents the damping ratios each part.

Finally, damping matrix of hybrid structure would be the summation of 3 base matrices as in Eq. (6) that its ratios are from mass proportionality and stiffness of the overall damping matrix of 3-DOF structure.

$$C = \sum_i C^i, \quad i = p, t, s \tag{6}$$

Special frequencies' ratio R_ω and weight ratio R_m are defined as in Eq. (7) in order to specify the system response according to the features of three constituents.

$$R_{\omega 1} = \frac{\omega_s}{\omega_p},\ R_{m1} = \frac{M_s}{M_p},\quad R_{\omega 2} = \frac{\omega_t}{\omega_s},\ \ R_{m2} = \frac{M_t}{M_s} \tag{7}$$

In this stage, a time history analysis is applied for equivalent 3-DOF structure according to Eq. (8) in order to obtain the equivalent modal damping ratio and its error.

$$M\{\ddot{y}\} + C\{\dot{y}\} + K\{y\} = -Mr\ddot{x}_g \tag{8}$$

In the Eq. (8), $\{y\}$ is relative displacement vector of MDOF structure, $\ddot{x}_g$ is excitation acceleration and r is equal to $\begin{bmatrix}1\\1\\1\end{bmatrix}$. The obtained results are equal to the overall acceleration and displacement in each level. Energy balance equation is defined by multiplying matrix transpose $\{\dot{y}\}$ in Eq. (8), as follows

$$\frac{d}{dt}\left(\frac{1}{2}\{\dot{y}\}^{\mathrm{T}}\, M\{\dot{y}\} + \frac{1}{2}\,\{\mathrm{y}\}^{\mathrm{T}}\, K\,\{\mathrm{y}\}\right) = -\{\dot{y}\}^{\mathrm{T}}Mr\ddot{x}_g - \{\dot{y}\}^{\mathrm{T}}\, C\{\dot{y}\} \tag{9}$$

Eq. (8) is reviewed in the state-space. The state-space method is based on transforming the N second-order coupled equations into a set of 2N first-order coupled equations (Newland 1989, Foss 1958). Equations of dynamic system motion can be recast as

$$A\dot{u}(t) + Bu(t) = F(t) \tag{10-1}$$

where A,B $\in \mathrm{R}^{2\mathrm{N}\times 2\mathrm{N}}$ are the system matrices, $F(t) \in \mathrm{R}^{2\mathrm{N}}$ the force vector and u$\in \mathrm{R}^{2\mathrm{N}}$ is the response vector in the state-space. The parameters of the equation 10-1 are obtained from Eq. (10-2).

$$A = \begin{bmatrix} C & M \\ M & O_N \end{bmatrix}, B = \begin{bmatrix} K & O_N \\ O_N & -M \end{bmatrix}, F(t) = \begin{Bmatrix} -Mr\ddot{x}_g \\ O_{N\times 1} \end{Bmatrix}, u(t) = \begin{Bmatrix} y(t) \\ \dot{y}(t) \end{Bmatrix} \tag{10-2}$$

In the equation above, O_N is the $N \times N$ null matrix.

The advantage of this approach is that the system matrices in the state-space retain symmetry as in the configuration space. It should be noted that these solution procedures have exact equivalents in nature.

New eigenvalues are obtained from Eq. (11).

$$B\Phi_i = -s_i A\Phi_i,\ i = 1,2,3,4,5,6 \tag{11}$$

In Eq. (11), s_i presents eigenvalues and Φ_i presents special vectors of complex numbers. Finally, modal damping ratio is calculated from Eq. (12).

$$\xi_i = \frac{-Re(s_i)}{|s_i|}, i = 1,2,3 \tag{12}$$

The obtained modal damping ratios are depicted in Figs. 3 to 17 for the first, second and third modes according to the previous equations in the proposed method. Colored contours represent damping ratio of hybrid structure in the three main modes. These graphs can be used in determining damping ratios of the hybrid buildings with transitional storey(s). In the first assumption in drawing the graphs, the equivalent damping is equal to 5% for the primary structure and equal to 7% for transitional storey, while for the third structure is considered equal to 2%. Eq. (7) is used in calculating frequency and mass ratios. $R_{\omega 2}$ and R_{m2} ratios are shown in top of graphs. Modal damping ratios of the three modes over the (R_{m1}-R_{w1}) plane are resulted.

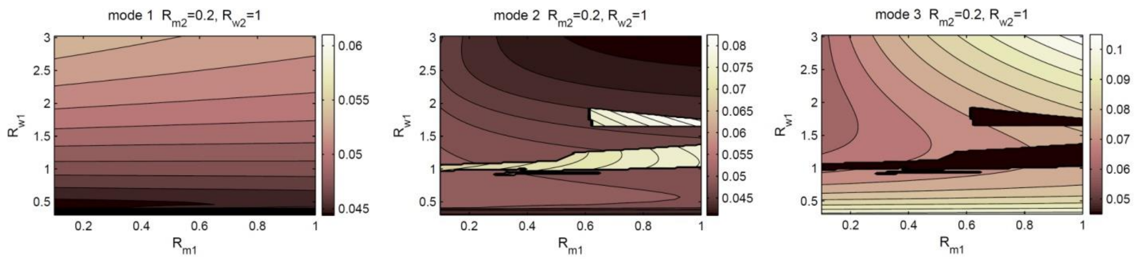


Fig. 3 The obtained modal damping ratio for R_{m2}= 0.2 and R_{w2}= 1

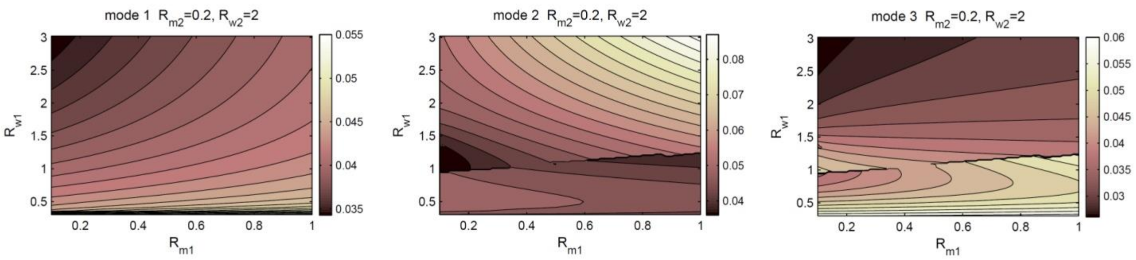


Fig. 4 The obtained modal damping ratio for R_{m2}= 0.2 and R_{w2}= 2

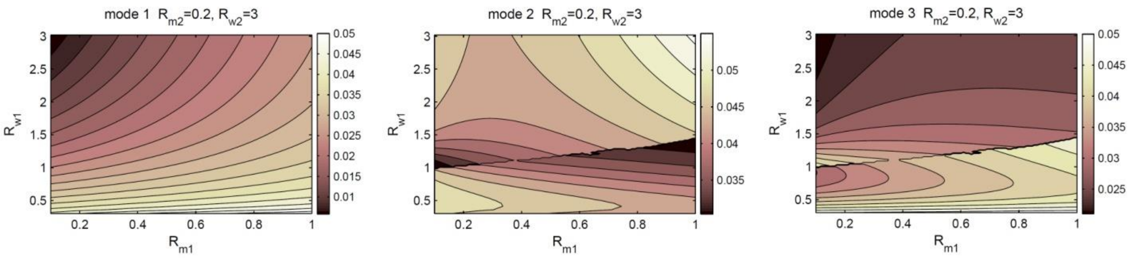


Fig. 5 The obtained modal damping ratio for R_{m2}= 0.2 and R_{w2}= 3

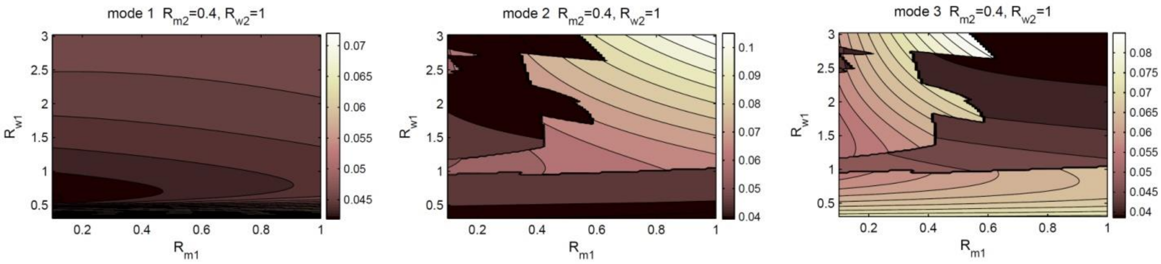


Fig. 6 The obtained modal damping ratio for R_{m2}= 0.4 and R_{w2}= 1

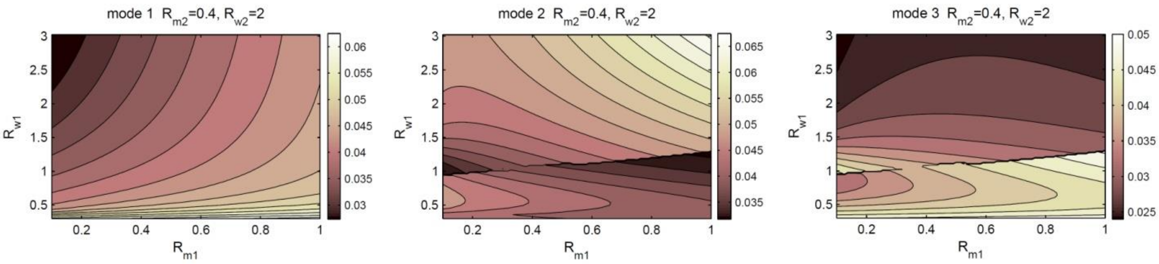


Fig. 7 The obtained modal damping ratio for R_{m2}= 0.4 and R_{w2}= 2

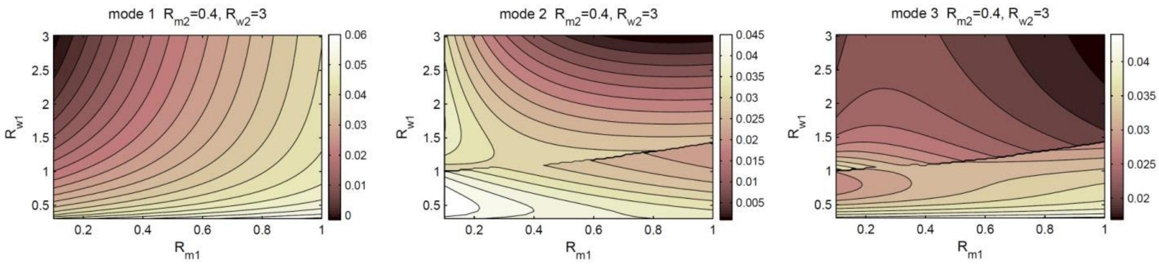


Fig. 8 The obtained modal damping ratio for R_{m2}= 0.4 and R_{w2}= 3

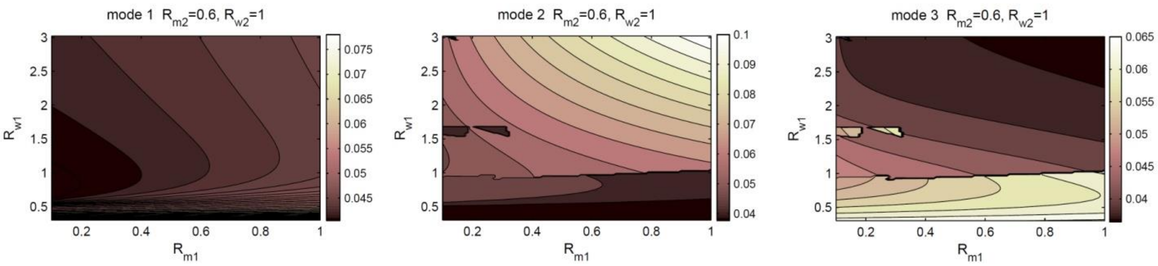


Fig. 9 The obtained modal damping ratio for R_{m2}= 0.6 and R_{w2}= 1

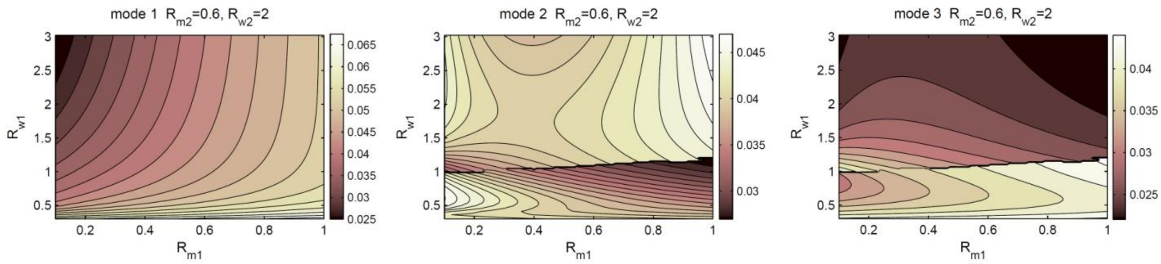


Fig. 10 The obtained modal damping ratio for R_{m2}= 0.6 and R_{w2}= 2

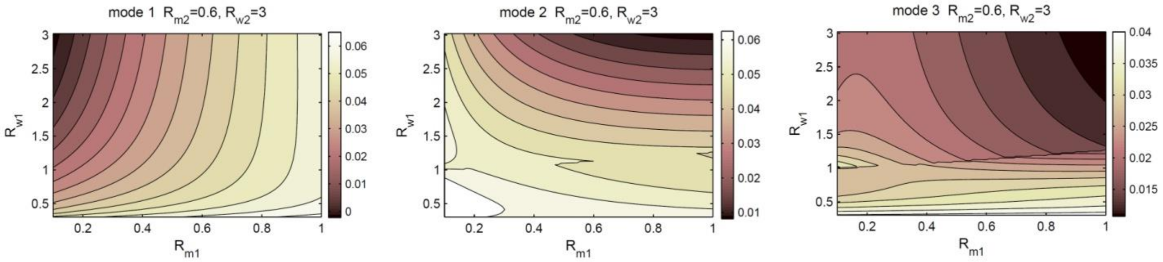


Fig. 11 The obtained modal damping ratio for R_{m2}= 0.6 and R_{w2}= 3

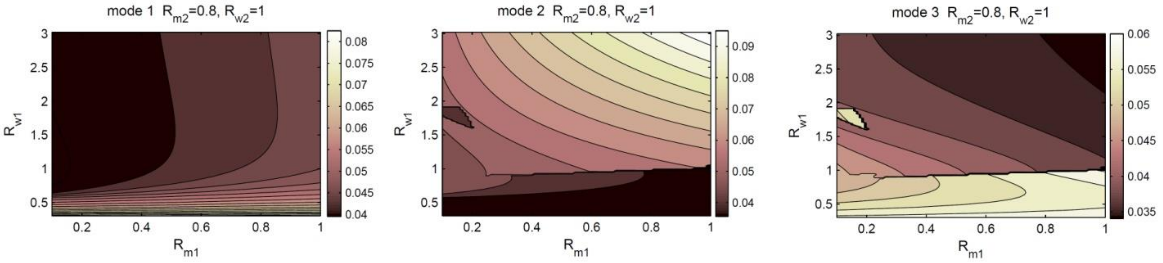


Fig. 12 The obtained modal damping ratio for R_{m2}= 0.8 and R_{w2}= 1

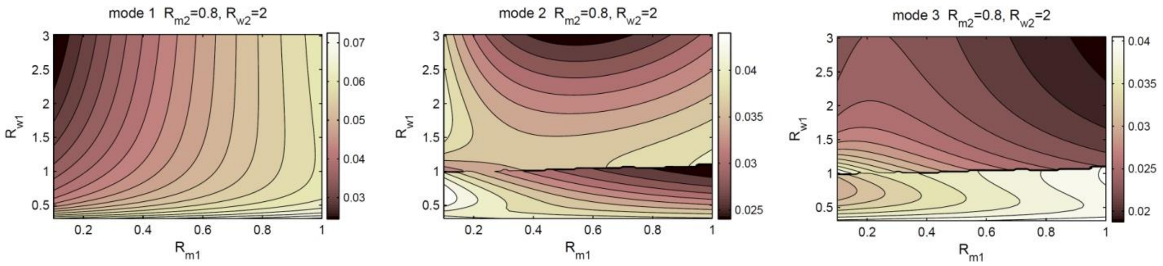


Fig. 13 The obtained modal damping ratio for R_{m2}= 0.8 and R_{w2}= 2

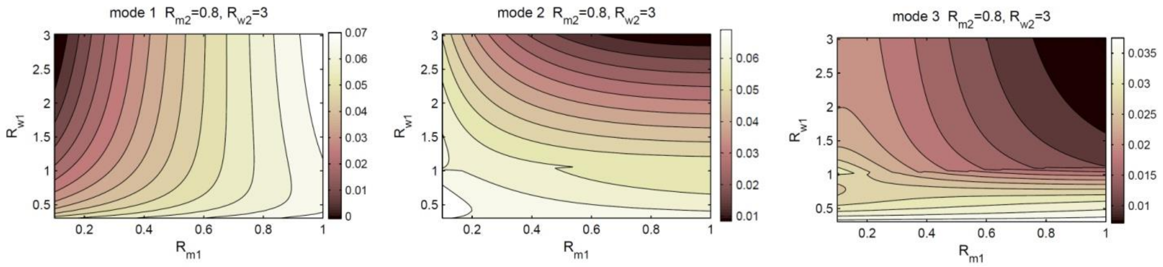


Fig. 14 The obtained modal damping ratio for R_{m2}= 0.8 and R_{w2}= 3

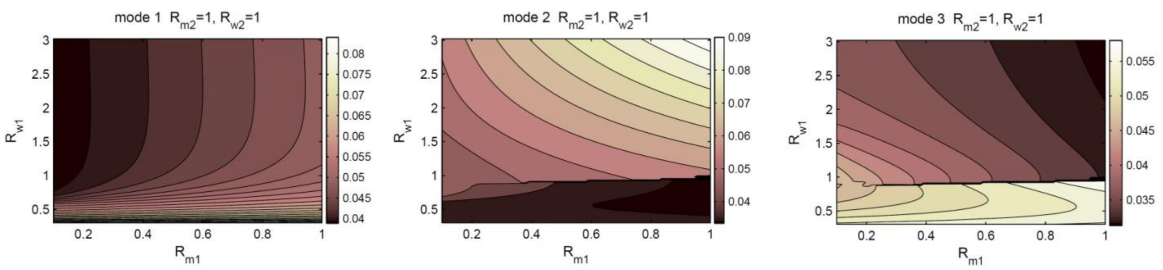


Fig. 15 The obtained modal damping ratio for R_{m2}= 1 and R_{w2}= 1

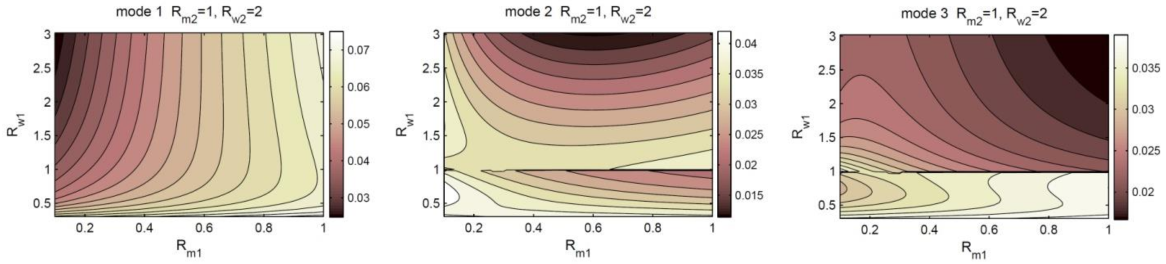


Fig. 16 The obtained modal damping ratio for R_{m2}= 1 and R_{w2}= 2

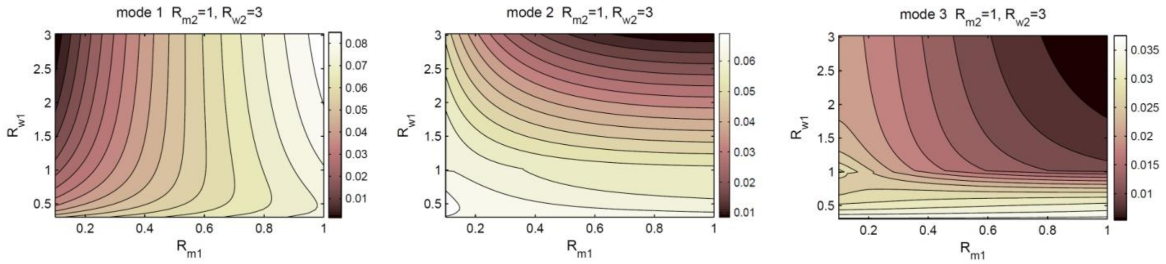


Fig. 17 The obtained modal damping ratio for R_{m2}= 1 and R_{w2}= 3

The proposed numerical method and graphs are a relatively precise method, because all of the modal quantities such as modal mass, M_i, and modal eigenvalues, Φ_i are obtained from real eigenvalues analysis (Papageorgiou and Gantes 2005).

4. Calculating the error in harmonic response

The most widely used approximation method in the dynamic analysis of structures with non-classical damping has always been the uncoupled mode superposition method. Clearly, the approximation made in this method is valid if modal coupling can be approximately ignored. It was concluded that under harmonic loading in these structures, the major error introduced by the decoupling approximation depends on transformed damping matrix, natural frequencies and etc. In the recent years, several studies have been presented investigating the conditions under which off-diagonal terms of the transformed damping matrix may be ignored. The configuration of each sub-structure is totally different with other ones, so calculating response of each substructure and its corresponding error is necessary for sake of precise analysis.

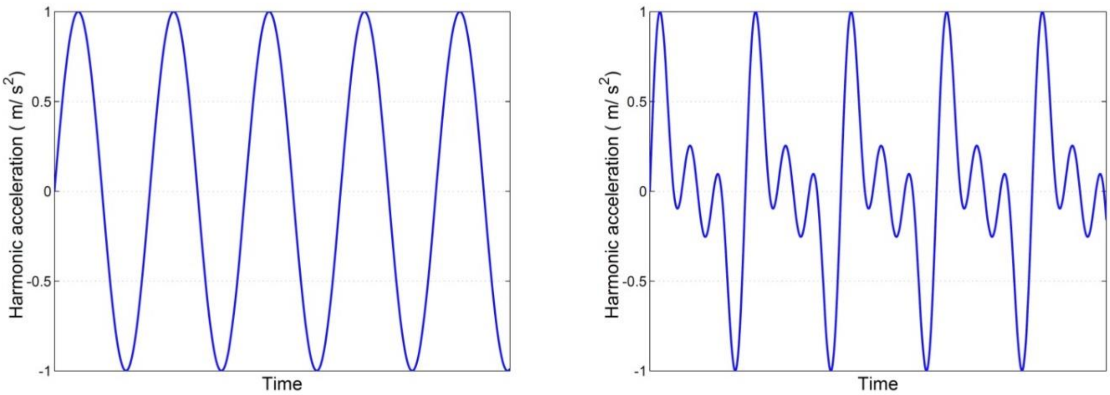
In the exact methods complex eigensolution is avoided. When the structure excitation is harmonic in Eq. (8), the receptance matrix $[\alpha]$ can be written as

$$[\alpha] = [[K] - \omega^2[M] + i[C]]^{-1} \tag{13}$$

where ω is the excitation frequency and i is the unit imaginary number. Obviously, for small ordered systems harmonic response of a system can directly be obtained by using the above equation and the definition of receptance matrix given in Eq. (14).

$$\{y(t)\} = [\alpha]\,\{F(t)\} \tag{14}$$

In exact method the damping matrix for the complete system is constructed by directly



(a) (b)

Fig. 18 Harmonic accelerations considered, (a) in resonance with the first mode of the 3-DOF structure and (b) hybrid harmonic motion

assembling the damping matrices for three structures. The stiffness and mass matrices of the combined structures are assembled from corresponding matrices for the three systems. The portion of these matrices associated with the common DOFs at the interface between two system included contributions from both systems (Chopra 2005). Using the exact method for dynamic analyzing of non-classically damped buildings is so much complicate and impossible. Exact methods have two primary disadvantages: they require significant numerical effort to determine the eigen-solutions, and little physical insight is afforded by methods that are purely numerical. Depending on the order of the system, the cost of complex matrix inversion will be much higher compared to that of complex mode superposition. Also, the best solution is to use approximation methods (Adhikari 2000, Özgüven 2002). Shahruz (1990) concluded that if the off-diagonal elements of damping matrix are smaller than diagonal elements, then the approximate solution is close to the exact solution. Shahruz and Langari (1992) in their investigations concluded that if the off-diagonal elements of damping matrix are sufficiently small and if the approximately decoupled systems are reasonably damped, then the approximate and exact results are close to each other. Park *et al*. (1992) concluded that the location of the excitation frequency with respect to the natural frequencies is the most important parameter for modal coupling. Duncan and Taylor (1979) have shown that significant errors occur, when dynamic analysis of a non-proportionally damped system is based on a truncated set of modes, as it is commonly performed in modeling continuous systems.

In the approximation method, the equivalent 3-DOF oscillator is separated into its three modes that each of them is stimulated again by $\ddot{x}_g$ according to Eq. (15).

$$\ddot{q}_i + 2\xi_i\omega_i\dot{q}_i + \omega_i^2 q_i = -\Gamma_i\ddot{x}_g \tag{15}$$

In the Eq. (15), Γ_i is modal participate factor. The response of Eq. (8) is obtained from Eq. (16).

$$y' = \Phi q \tag{16}$$

The final response is the overall displacement in each storey so that the equation $\{\ddot{\bar{y}}'\} = \{\ddot{y}'\} + \{r\}\ddot{x}_g$ is established (Papageorgiou and Gantes 2010, Foss 1958, Özgüven 2002). Error value in each level of the overall acceleration and displacement responses is obtained from Eq. (17).

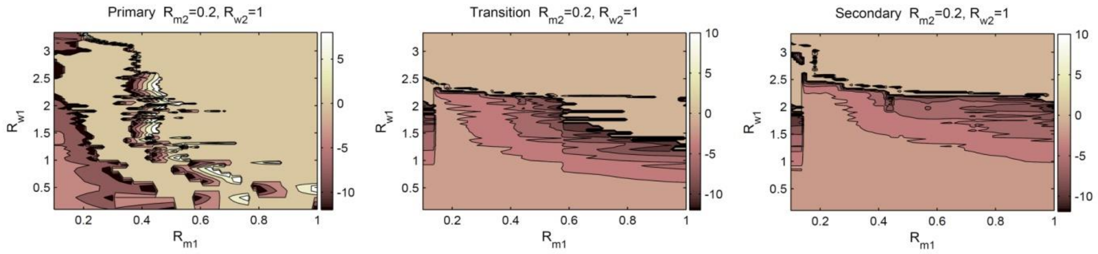


Fig. 19 Error in harmonic excitation, for R_{m2}=0.2 , R_{w2}=1

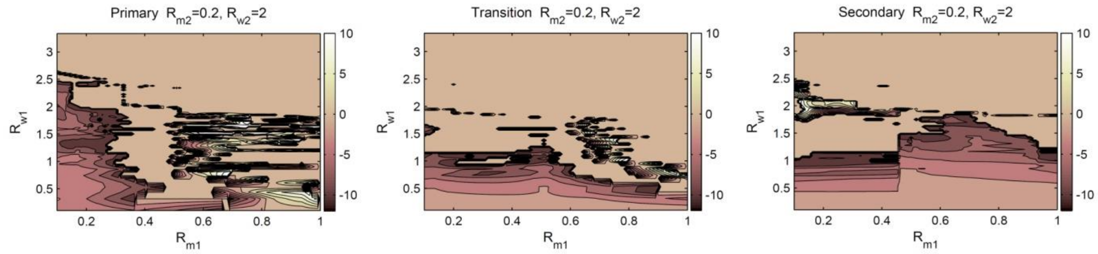


Fig. 20 Error in harmonic excitation, for R_{m2}=0.2 , R_{w2}=2

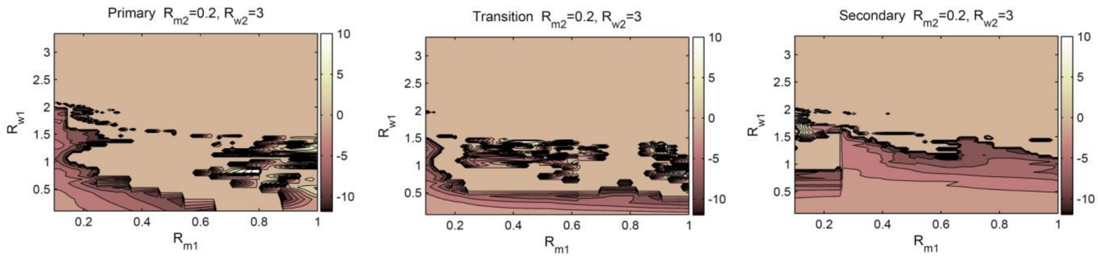


Fig. 21 Error in harmonic excitation, for R_{m2}=0.2, R_{w2}=3

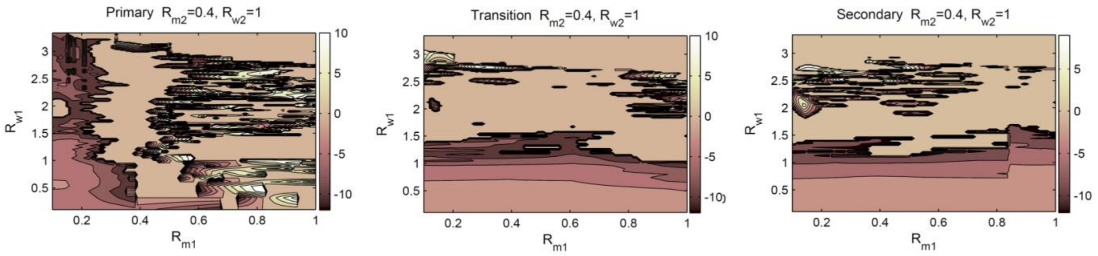


Fig. 22 Error in harmonic excitation, for R_{m2}=0.4 , R_{w2}=1

$$e_{dis} = \frac{\max(|y_i|) - \max(|y_i'|)}{\max(|y_i|)} \tag{17}$$

For assessment of errors, acceleration is selected to be harmonic in resonance with the first mode of the 3-DOF structure, as shown in Eq. (18-1) and Fig. 18(a). Moreover, a hybrid motion is created by adding three separate motions, each in resonance with one mode of the structure, and scaling the final motion to have again amplitude as in Eq. (18-2) and Fig. 18(b).

$$a_1 = sin\,\omega_1 t \tag{18-1}$$

$$a_2 = sin\,\omega_1 t + sin\,\omega_2 t + sin\,\omega_3 t \tag{18-2}$$

Error plots in displacements of hybrid harmonic excitation are shown for primary structure, transitional storey and secondary structure in Figs. 19-33.

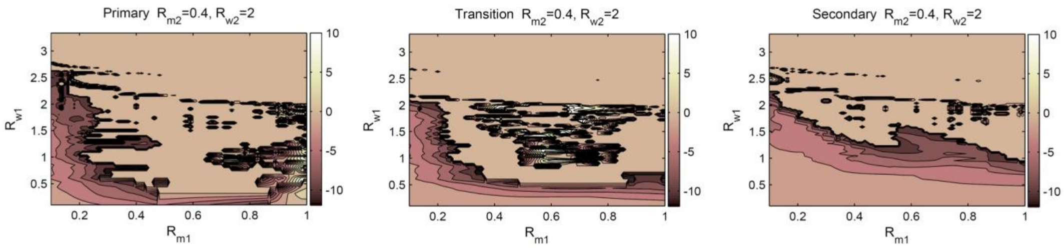


Fig. 23 Error in harmonic excitation, for R_{m2}=0.4 , R_{w2}=2

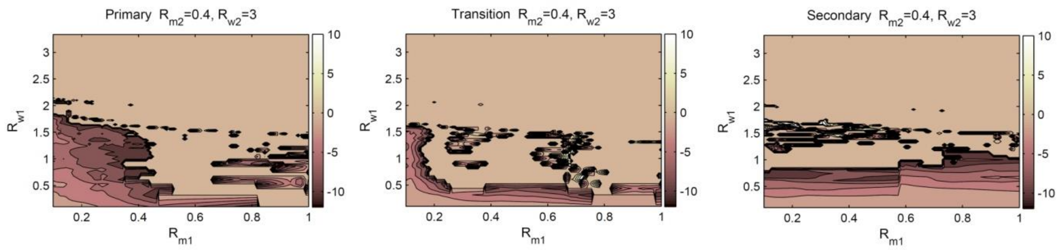


Fig. 24 Error in harmonic excitation, for R_{m2}=0.4 , R_{w2}=3

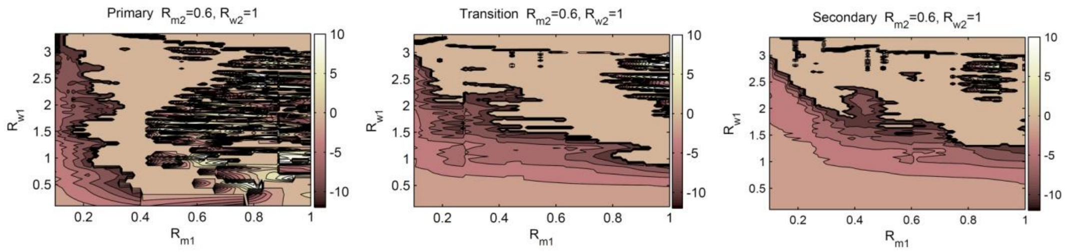


Fig. 25 Error in harmonic excitation, for R_{m2}=0.6 , R_{w2}=1

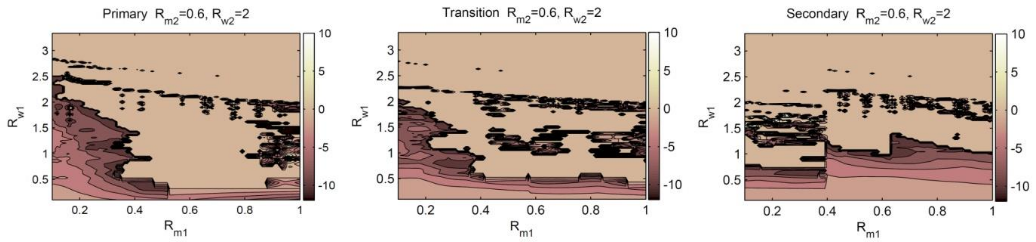


Fig. 26 Error in harmonic excitation, for R_{m2}=0.6 , R_{w2}=2

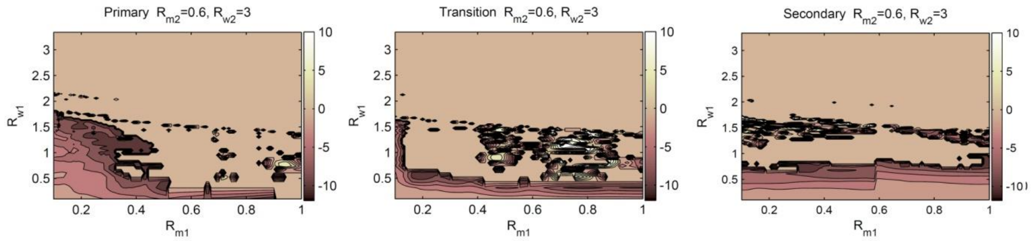


Fig. 27 Error in harmonic excitation, for R_{m2}=0.6, R_{w2}=3

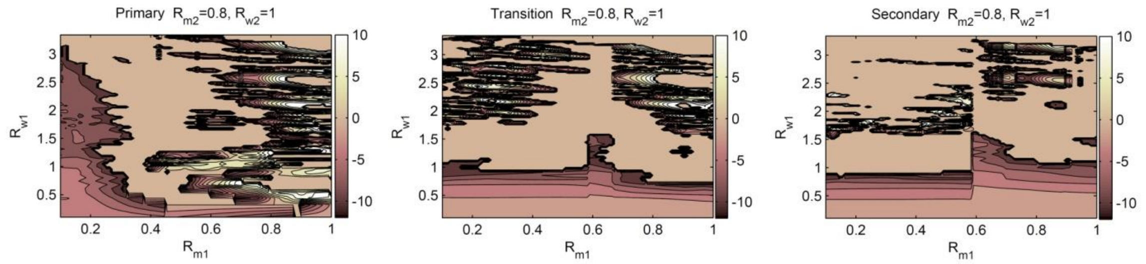


Fig. 28 Error in harmonic excitation, for R_{m2}=0.8 , R_{w2}=1

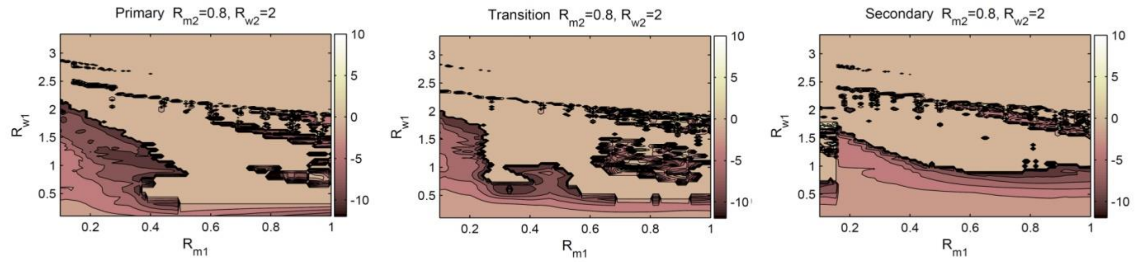


Fig. 29 Error in harmonic excitation, for R_{m2}=0.8 , R_{w2}=2

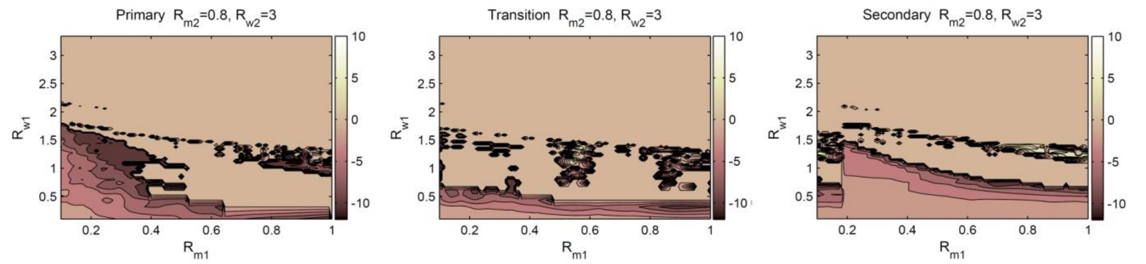


Fig. 30 Error in harmonic excitation, for R_{m2}=0.8 , R_{w2}=3

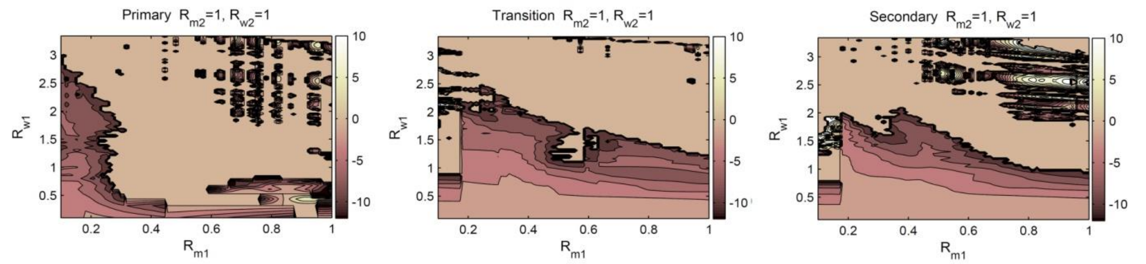


Fig. 31 Error in harmonic excitation, for R_{m2}=1 , R_{w2}=1

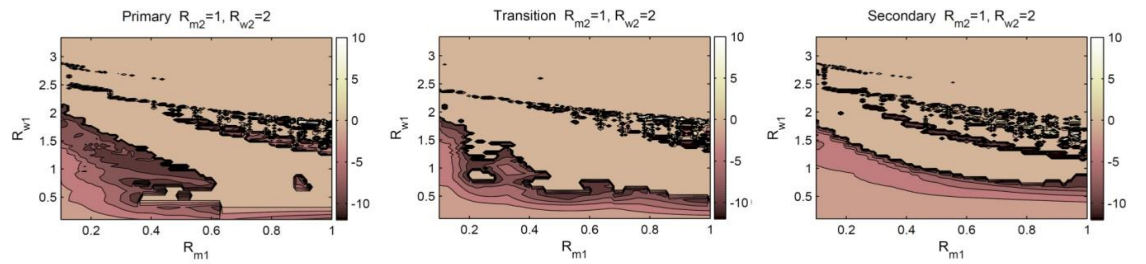


Fig. 32 Error in harmonic excitation, for R_{m2}=1 , R_{w2}=2

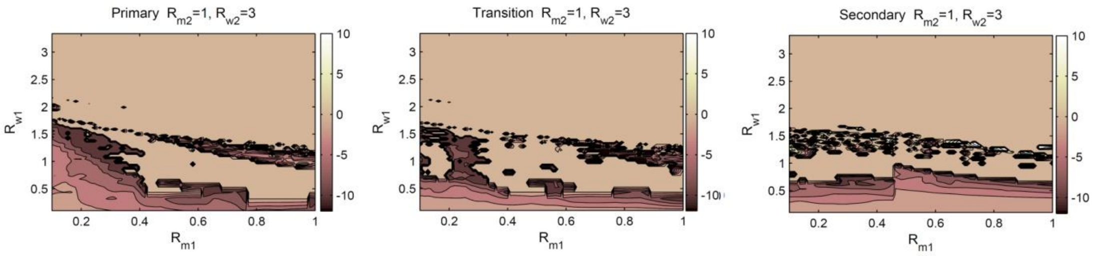


Fig. 33 Error in harmonic excitation, for R_{m2}=1 , R_{w2}=3

Table 1 Cross section for members of building

Story	Structure	System	Columns (cm)	Beams (cm)
1-2	primary	RC	60×60, ρ_t=0.022	40×60, ρ_s=0.012, ρ'_s=0.009
3-4	primary	RC	50×50, ρ_t=0.0197	40×50, ρ_s=0.00682, ρ'_s=0.0051
5	transition	composite	50×50, ρ_t=0.0197+BOX 30×30×0.1	IPE 300
6-7-8	secondary	steel	BOX 30×30×0.1	IPE 300
9-10	secondary	steel	BOX 25×25×0.08	IPE270

Table 2 Modal characteristics of building

Mode	Period(s)	Modal Participate Factor (%)	Frequency (rad/s)
1	1.395	58.739	4.504
2	0.612	22.9821	10.267
3	0.352	5.12	17.85
4	0.207	4.0791	30.354
5	0.161	2.538	39.026
6	0.12	1.8312	52.36
7	0.099	1.57	63.466
8	0.074	1.3398	84.908
9	0.061	1.043	103.003
10	0.05	0.7643	125.664

5. Validation and the application of the proposed method for seismic analysis

In the method proposed in this study, the effect of transitional storey has also been considered for determining modal damping in hybrid structures. Therefore, reviewing structure's dynamic behavior by the proposed method is closer to the behavior of the real structure. A ten-storey building was analyzed for validity of the proposed method and modal damping ratios were calculated both by the proposed method by Papageorgiou and Gantes (2010) and the proposed method in this study and also fixed ratios 2% and 5%. Properties of this building are shown in Table 1.

Transitional storey's columns also have compound section of its upper storey's steel section and lower storey's concrete section. Modal participate ratio and period of designed structure are shown in Table 2.

For time history analysis of the designed structure, three earthquake records (Bam, Elcentro

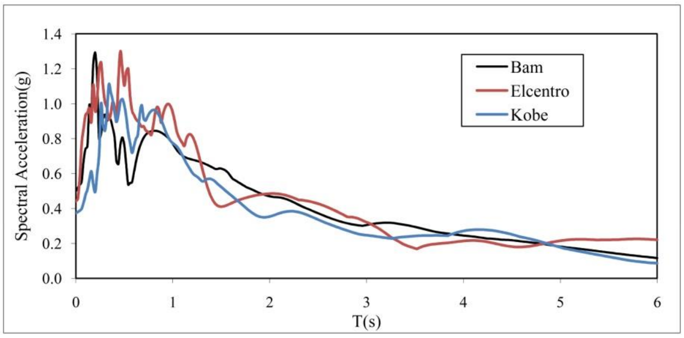
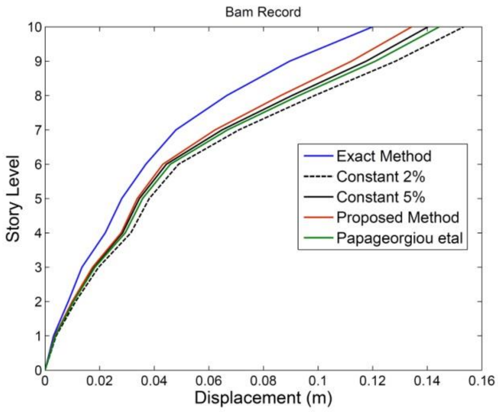
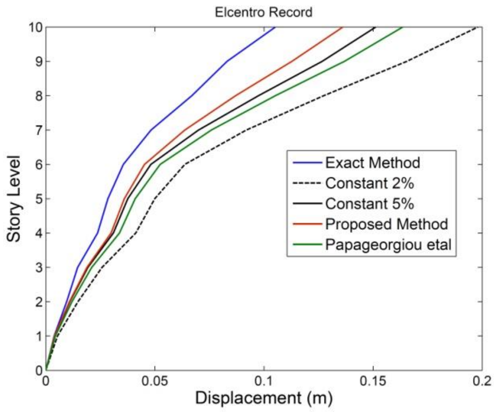


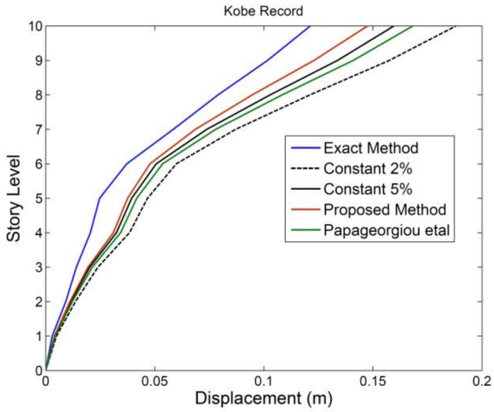
Fig. 34 Response spectrum of the selected records for time history analysis



(a)



(b)



(c)

Fig. 35 Comparison of the obtained damping effect from the proposed method and other methods in the structure's dynamic response for (a) Bam (b) Elcentro (c) Kobe earthquake

and Kobe) were selected. Fig. 34 shows the response spectrums of these earthquakes.

The values of Rm_1, Rw_1, Rm_2 and Rw_2 were calculated equal to 0.38, 0.77, 0.81 and 2.93, respectively. Modal damping ratios were obtained 6.61%, 2.64% and 3.56% for the first, second and third modes, respectively.

Fig. 35 shows the maximum response of the structure calculated according to the obtained damping from the proposed method and graphs, the presented relation by Papageorgiou and Gantes (2010), constant damping ratios 2 and 5 percent and also exact method.

In order to apply equivalent damping ratio proposed by Papageorgiou and Gantes (2010), the transitional story was considered as a part of reinforced concrete structure. The stiffness of transitional storey is much more than both primary structure and secondary one. Also the interaction between transitional storey and other sub-structures causes that the response of transitional storey influences on response of other parts. Accordingly, the damping ratio of 7% has a great influence on response of whole structure, thus the case of overall damping ratio equals to 5% overestimates the exact behavior of structure.

It can be observed that, proposed method in this study is closer to the real response of the structure and has more care and credit than recent methods. Therefore, it is suggested that the proposed graphs in this study can be used in calculating modal damping ratios for analysis of hybrid buildings with transitional storey.

6. Conclusions

Different applications and conditions of the structures necessitate using concrete and steel hybrid systems in some cases. One or more transitional storey is used in hybrid structures for better transition of lateral and gravity forces. The available design regulations have not presented a method for determining the damping of these structural systems which can cause some problems in designing these structures. Also, the existence of different damping has made it more complicated to assess the seismic response of hybrid structures in earthquakes. Several studies have been conducted in recent years about damping of these structures and some methods have been proposed to determine the damping of hybrid structures. The effect of transitional storey has not been considered in any of studies and it makes a big difference between the response of the analyzed structure and the real response. In this paper a method was proposed for determining equivalent modal damping ratio of hybrid buildings by considering the effect of the transitional storey and some graphs were also extracted. Error in harmonic loadings in nonlinear dynamic analysis of hybrid structures was obtained. Validation of the proposed method with exact method and also the former methods showed the high accuracy of the proposed method.

References

Adhikari, S. and Wagner, N. (2004), "Direct time-domain integration method for exponentially damped linear systems", *J. Comput. Struct.*, **82**(29-30), 2453-2461.

Adhikari, S. (2000), "Damping models for structural vibration", Ph.D. Thesis, University of Cambridge.

Basu, A.K. and Sommerville, W. (1996), "Derivation of formulae for the design of rectangular composite columns", *Proceeding of Civil Engineering Department*, London.

Chopra, A.K. (1995), *Dynamics of structures: theory and application to earthquake engineering*, Prentice-Hall, Upper-Saddle River, NJ.

Clough, R.W. and Penzien, J. (1993), *Structural dynamics*, New York, McGraw Hill.

Computers and Structures Inc. SAP (2000), Integrated Structural Analysis and Design Software, Berkeley, CA. (http://www.csiberkeley.com/sap2000)

Cortes, F., Mateos, M. and Elejabarrieta, M.J. (2009), "A direct integration formulation for exponentially

damped structural systems", *J. Comput. Struct.*, **87**(5-6), 391-394.
Duncan, P.E. and Taylor, R.E. (1979), "A note on the dynamic analysis of non-proportionally damped systems", *J. Earthq. Eng. Struct. Dyn.*, **7**(1), 99-105.
Fang, J.Q., Li, Q.S., Jeary, A.P. and Liu, D.K. (1999), "Damping of tall buildings: its evaluation and probabilistic characteristics", *J. Struct. Des. Tall Spec. Build.*, **8**(2), 145-153.
Foss, K.A. (1958), "Co-ordinates which uncouple the equations of motion of damped linear dynamic systems", *Tran. ASME, J. Appl. Mech.*, **25**, 361-364.
Hajjar, J.F. (2002), "Composite steel and concrete structural systems for seismic engineering", *J. Constr. Steel Res.*, **58**(5-8), 703-723.
Huang, B.C., Leung, A.Y.T., Lam, K.L. and Cheung, V.K. (1996), "Analytical determination of equivalent modal damping ratios of a composite tower in wind-induced vibrations", *J. Comput. Struct.*, **59**(2), 311-316.
Johnson, R.P. (2004), *Composite Structures of Steel and Concrete*, Blackwell Scientific Publications.
Kim, M.C., Jung, H.J. and Lee, I.W. (1999), "Solution of eigenvalue problem for non-classically damped system with multiple frequencies", *J. Sound Vib.*, **219**(2), 196-111.
Lee, S.H., Min, K.W., Hwang, J.S. and Kim, J. (2004), "Evaluation of equivalent damping ratio of a structure with added dampers", *J. Eng. Struct.*, **26**(3), 335-46.
Li, Q.S., Yang, K., Zhang, N., Wong, C.K. and Jeary, A.P. (2002), "Field measurements of amplitude-dependent damping in a 79-storey tall building and its effects on the structural dynamic responses", *J. Struct. Des. Tall Spec. Build.*, **11**(2), 129-153.
Liu, S.W., Liu, Y.P. and Cha, S.L. (2012), "Advanced analysis of hybrid steel and concrete frames Part 1: Cross-section analysis technique and second-order analysis", *J. Constr. Steel Res.*, **70**, 326-336.
Mazzoni, S., McKenna, F., Scott, M.H. and Fenves, G.L. (2006), *The Open System for Earthquake Engineering Simulation (OpenSEES) User Command-Language Manual*, Pacific Earthquake Eng. Research Center, Univ. Calif., Berkeley, CA. (http://opensees.berkeley.edu)
Newland, D.E. (1989), *Mechanical Vibration Analysis and Computation*, Longman, Harlow and John Wiley, New York.
Özgüven, H.N. (2002), "Twenty Years of Computational Methods for Harmonic Response Analysis of Non-Proportionally Damped Systems", *Proceedings of the 20th International Modal Analysis Conference*, Los Angeles.
Papageorgiou, A. and Gantes, C. (2005), "Decoupling criteria for dynamic response of primary/secondary structural systems", *Proceedings of 4th European workshop on the seismic behavior of irregular and complex structures*, Thessaloniki, Greece.
Papageorgiou, A. and Gantes, C. (2010), "Equivalent modal damping ratios for concrete/steel mixed structures", *J. Comput. Struct.*, **88**(19-20), 1124-1136.
Papageorgiou, A. and Gantes, C. (2010), "Decoupling criteria for inelastic irregular primary/secondary structural systems subject to seismic excitation", *J. Eng. Mech.*, **136**(10), 1234-1247.
Papageorgiou, A. and Gantes, C. (2011), "Equivalent uniform damping ratios for linear irregularly damped concrete/steel mixed structures", *J. Soil Dyn. Earthq. Eng.*, **31**(3), 418-430.
Papagiannopoulos, G.A. and Beskos, D.E. (2006), "On a modal damping identification model of building structures", *Arch. Appl. Mech.*, **76**(7-8), 443-463.
Papagiannopoulos, G.A. and Beskos, D.E. (2009), "On a modal damping identification model for non-classically damped linear building structures subjected to earthquakes", *J. Soil Dyn. Earthq. Eng.*, **29**(3), 583-589.
Park, I.W., Kim, J.S. and Ma, F. (1992), "On modal coupling in non-classically damped linear systems", *Mech. Res. Commun.*, **19**(5), 407-413.
Shahruz, S.M. (1990), "Approximate decoupling of the equations of motion of damped linear systems", *J. Sound Vib.*, **136**(1), 51-64.
Shahruz, S.M. and Langari, G. (1992), "Closeness of the solutions of approximately decoupled damped linear systems to their exact solutions", *ASME J. Dyn. Syst., Measur. Control*, **114**(3), 369-374.
Taranath, B.S. (2011), *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*,

DeSimone Consulting Engineers, Nevada.

Viest, I.M., Colaco, J.P., Furlong, R.W., Griffs, L.G., Leon, R.T. and Wyllie, L.A. (1997), *Composite Construction Design for Buildings*, ASCE/McGraw-Hill.

Villaverde, R. (2008), "A complex modal superposition method for the seismic analysis of structures with supplemental dampers", *Proceedings of the 14th World Conference on Earthquake Engineering*, 14WCEE, Beijing, China.

Virdi, K.S. and Dowling, P.J. (1973), "The ultimate strength of composite columns in biaxial bending", *ICE Proceedings*, 55(10), 251-272.

Xu, J. (2004), "A synthesis formulation of explicit damping matrix for non-classically damped systems", *Nucl. Eng. Des.*, **227**(2), 125-132.

Zona, A., Barbato, M. and Conte, J.P. (2008), "Nonlinear seismic response analysis of steel-concrete composite frames", *J. Struct. Eng.*, **134**(6), 986-997.