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# THE SEISMIC RESPONSE CHARACTERISTICS OF A NEW STRUCTURAL CONFIGURATION

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**ABSTRACT :**

In this paper a new kind of structural configuration, named passive mega-sub controlled structure (PMSCS), is presented, which is constructed by applying the structural control principle into structural configuration itself, to form a new structure with obvious response self-control ability. In the analysis of PMSCS the equations of motion of the seismically excited system are developed. The seismic response control effectiveness of the proposed PMSCS under stationary and nonstationary random processes was evaluated by comparing its seismic response with the response of its conventional (uncontrolled) mega-sub structure counterpart. A parametric study of the relative stiffness between the mega-frame and substructure of the PMSCS is presented and discussed. The region over which these structural characteristics yield the optimum seismic response control of the PMSCS is identified and serves as a very useful design tool for practitioners. The results show that the proposed PMSCS offers an effective means of controlling the seismic displacement and acceleration response of tall/super-tall mega-systems.

**KEYWORDS**: Passive mega-sub controlled structure, seismic excitation, structure response, controlling effectiveness, relative stiffness

## 1. INTRODUCTION

One of the major engineering challenges in the design structures is to ensure their structural integrity under extreme earthquake and wind loads, and their human comfort under normal wind loads. Mega-sub structure (MSS) is a new configuration form of super tall building appeared recently. The MSS consists of two major components: a mega-frame, which is the main structural frame in the building, and several substructures are rigidly connected to the mega-frame, each containing many storeys that are used for commercial and/or residential purposes, as shown in Fig.1. In this paper, a new passive mega-sub controlled structure (PMSCS) configuration is proposed based on conventional MSS， as shown in Fig.2. In the design of the PMSCS, the connections between the mega-building and the substructures were released, these sub structures are designed as isolated sub structures, whose function is similar to that of the conventional tuned mass damper system in principle. It acts to convert the traditional MSS into a huge, self-controlled, passive mega-sub controlled structure that is capable of developing very high control energy to control the responses induced in the PMSCS by these natural forces by the structure itself. The mass ratio between the sub and mega structures is much higher (as high as 100%) than that in the tuned mass damper system (usually 1%). It is this feature that makes the proposed structure to control the responses much more effective. To overcome shortcomings exhibited in earlier proposed mega-sub controlled structural configurations by other scholars [Feng and Mita 1995, Chai and Feng 1997, Lan et al 2002], additional columns are introduced at the top-level of some of the substructures serve to eliminate the shortcomings associated with the excessively large-span mega-beams. In addition, dampers (or named as added dampers) are installed between the mega-frame and its substructures to prevents pounding between the mega-frame and its substructures.

In this paper, the dynamic behavior and the response control effectiveness of this new proposed PMSCS under seismic excitations is examined. A parametric study of the structural characteristics that influence the response control of this system is undertaken and leads to the definition of the structural parameter region that should be satisfied to ensure optimum seismic response control.

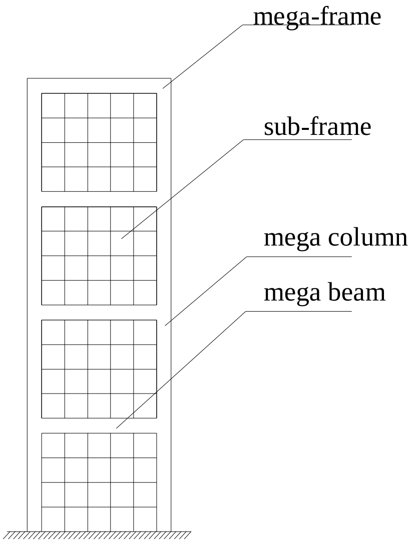



Figure 1 The conventional mega-sub structure

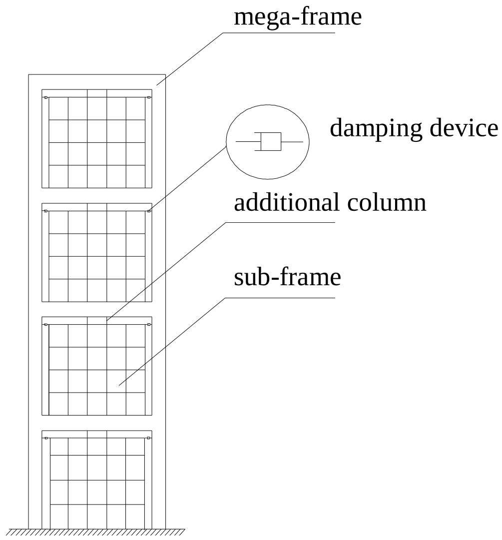



Figure 2 The new PMSCS configuration

## 2. EQUATIONS OF MOTION OF PASSIVE MEGA-SUB CONTROLLED STRUTURE UNDER SEISMIC EXCITATION

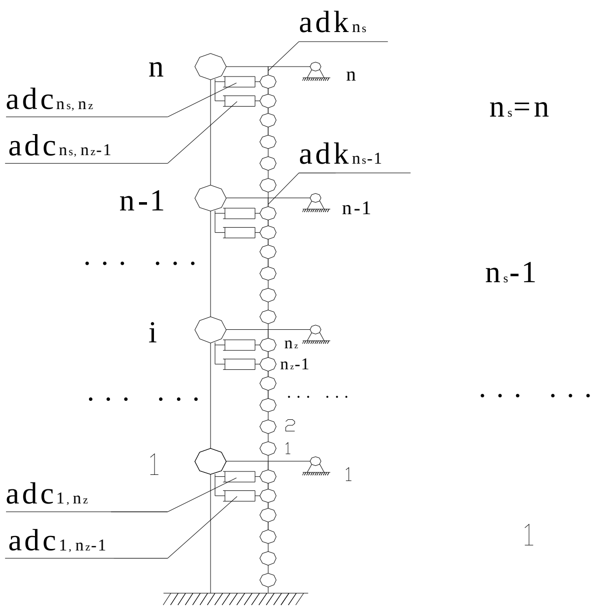



Figure 3 The computing model of the new PMSCS

In this proposed PMSCS, both the mega-frame and its substructures are modeled as MDOF systems, as shown in Fig.3, $adc_{i,k}$ is added damping value and $adk_i$ is additional columns stiffness value. A PMSCS having $n$ mega-storeys and $n_s$ substructures, each of which consists of $n_z$ storeys moving relative to the mega-frame, will have a total of $N= n+n_s \times n_Z$ degrees-of-freedom. The relative-response equations of motion for this system under seismic ground motions can be expressed as:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = -\boldsymbol{\Gamma}\ddot{x}_g \tag{2.1}$$

where, $\boldsymbol{X} = [\boldsymbol{x}_p^{\mathrm{T}}, \boldsymbol{x}_1^{\mathrm{T}}, \boldsymbol{x}_2^{\mathrm{T}}, \ldots\ldots, \boldsymbol{x}_{n_S}^{\mathrm{T}}]^{\mathrm{T}}$ is the lateral deformation vector of the system relative to its moving base, with $n + n_s n_z$ variables, and $\boldsymbol{x}_p = [x_{p,1}, x_{p,2}, \cdots, x_{p,n}]^{\mathrm{T}}$, $\boldsymbol{x}_i = [x_{i,1}, x_{i,2}, \cdots, x_{i,n_z}]^{\mathrm{T}}$ ($i$=1,2,…, $n_s$) are the lateral deformation vectors of the mega-frame and $i^{\mathrm{th}}$ substructure, respectively. ***M*, *K*, *C*** and $\boldsymbol{\Gamma}$ expresses the global mass matrix, stiffness matrix, damping matrix and mass vector of the system respectively [Zhang X. A., Zhang J. and et al 2005], and $\ddot{x}_g$ is the simulated seismic ground acceleration at the base of the structure. In the present study, in equation. (2.2), $\ddot{x}_g$ is modeled as a stationary random process when $A(t)$=1 , or as a uniformly modulated random process, whose nonstationary properties offer a more reliable representation of the characteristics of real earthquake ground motions.

$$\ddot{x}_g = A(t) \cdot n(t) \tag{2.2}$$

where *n(t)* is the stationary random processes with zero mean, and *A(t)* is the modulating function that defines the nonstationary random process.

Through the numerical computing check, the equation (2.1) with the matrix $\boldsymbol{C}$ cannot be decoupled, as the decoupling necessary and sufficient condition [T.K.Caughey and M.E.J.O'Kelly (1965)] is not met. Hence, the complex modal analytical theory must be employed [Fang. T(1995)]. The power spectral density *(PSD)* of the $\boldsymbol{X}$ displacement vector $\boldsymbol{S}_X(\omega)$ and the acceleration vector $\boldsymbol{S}_{\ddot{X}}(\omega)$ can be obtained by deducing. For stationary random seismic excitation,

$$\boldsymbol{S}_X(\omega) = \boldsymbol{u} \cdot \boldsymbol{H}(-\omega) \cdot \boldsymbol{G} \cdot S_n(\omega) \cdot \overline{\boldsymbol{H}}(-\omega)^T \cdot \overline{\boldsymbol{u}}^T \tag{2.3}$$

$$\boldsymbol{S}_{\ddot{X}}(\omega) = \omega^4 \boldsymbol{S}_X(\omega) \tag{2.4}$$

where $\boldsymbol{u} = [\boldsymbol{u_1}, \boldsymbol{u_2}, \cdots, \boldsymbol{u_{2N}}]$ is the right eigenvector matrix, $\boldsymbol{G}$ is the coefficient matrix, $S_n(\omega)$ is the *PSD* of the stationary acceleration excitation acting on the base of the structural system, here the Kanai-Tajimi model is used, and $\boldsymbol{H}_i(-\omega)$ and $\overline{\boldsymbol{H}}_j(-\omega)$ are, respectively, the $i^{th}$ modal frequency function and $j^{th}$ modal conjugate frequency function of $-\omega$ [Zhang *et al* 2005].For nonstationary random seismic excitation, $\ddot{x}_g$ is chosen as the uniformly modulated random processes, and 'Shinozhuka-Sato' modulating function *A(t)* is adopted, such that

$$\boldsymbol{S}_X(t,\omega) = \boldsymbol{u} \cdot \boldsymbol{S}_Z(t,\omega) \cdot \overline{\boldsymbol{u}}^T \tag{2.5}$$

$$\boldsymbol{S}_{\ddot{X}}(\omega) = \boldsymbol{uP}[S_{\dot{Z}_i\dot{Z}_j}(\omega)]\overline{\boldsymbol{P}}^T\overline{\boldsymbol{u}}^T \tag{2.6}$$

$$S_{Z_{i,j}}(t,\omega) = g_{i,j} I_i(t,\omega) \bar{I}_j(t,\omega) S_n(\omega) \tag{2.7}$$

$$\begin{aligned} S_{\dot{Z}_{i,j}}(t,\omega) = g_{i,j} \cdot A(t)^2 \cdot S_n(\omega) + p_i \cdot S_{Z_{i,j}}(t,\omega) \cdot \bar{p}_j \; + \; p_i \cdot g_{i,j} \cdot I_i(t,\omega) \cdot S_n(\omega) \cdot A(t) \\ + g_{i,j} \cdot \bar{I}_j(t,\omega) \cdot S_n(\omega) \cdot A(t) \cdot \bar{p}_j \end{aligned} \tag{2.8}$$

where $S_n(\omega)$ is the *PSD* corresponding to *n(t)* in expression (2.2), $p_i$ is its $i^{th}$ eigenvalue, $g_{i,j}$ are the elements of the coefficient matrix $\boldsymbol{G}$, and $I_i(t,\omega)$ in equation.(2.7) and (2.8) can be expressed as:

$$I_i(t,\omega) = e^{p_i t}\left\{\frac{1}{-(p_i+\alpha_1+j\omega)}[e^{-(p_i+\alpha_1+j\omega)t}-1] + \frac{1}{(p_i+\alpha_2+j\omega)}[e^{-(p_i+\alpha_2+j\omega)t}-1]\right\} \tag{2.9}$$

where $\alpha_1, \alpha_2$ are two exponential parameters of $A(t)$.Finally, the displacement and acceleration mean square response values for stationary and nonstationary seismic excitation are:

$$\boldsymbol{\sigma_X}^2 = \int_{-\infty}^{\infty} \boldsymbol{S}_X(\omega) d\omega \tag{2.10}$$

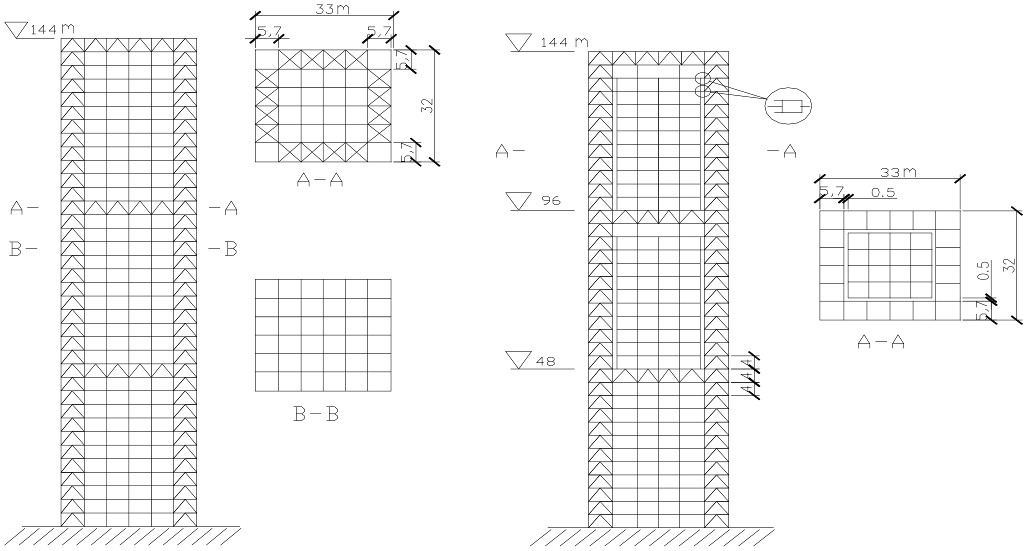
$$\boldsymbol{\sigma_{\ddot{X}}}^2 = \int_{-\infty}^{\infty} \boldsymbol{S}_{\ddot{X}}(\omega) d\omega \tag{2.11}$$

## 3. NUMERICAL EVALUATION OF THE SEISMIC RESPONSE PERFORMANCE OF AN EXAMPLE PASSIVE MEGA-SUB CONTROLLED STRUCTURE

To investigate the performance of the passive mega-sub controlled structure, with reference to the conventional mega-sub frame used in Tokyo City Hall presented in Fig. 4a, a steel passive mega-sub controlled frame is designed, as shown in Fig. 4b. The two buildings have the same amount of total mass and the same structural members as listed in the reference [Zhang X. A., Zhang J. and et al 2005]. The structure is comprised of three mega-storeys and three, 10-storey substructures. Here, the lateral connections between the substructures and the second and third storeys of the mega-frame have been released. The seismic response control effectiveness of the proposed PMSCS was evaluated by comparing its seismic response with the response of its conventional (uncontrolled) MSS counterpart, is a measure of the control effectiveness of the proposed PMSCS. In order to further examine the controlling effectiveness of this passive mega-sub controlled frame with different sub structural stiffness, the relative stiffness ratio *RK* between the mega frame and the sub structure are respectively defined as following:

$$RK = \frac{K^*_{sub}}{K^*_{mega}} \tag{3.1}$$

Where $K^*_{sub}$ the shear stiffness of sub structure, and $K^*_{mega}$ the bending stiffness of mega frame.

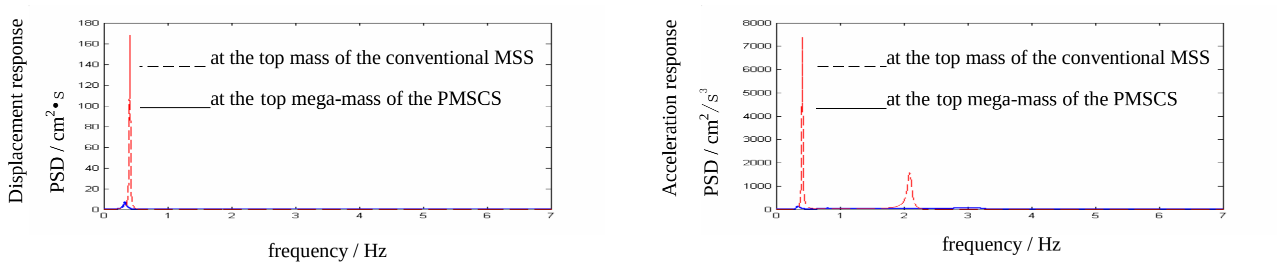



(a) The conventional steel MSS configuration (b) The steel MSCS configuration

Figure 4 The two structural configurations

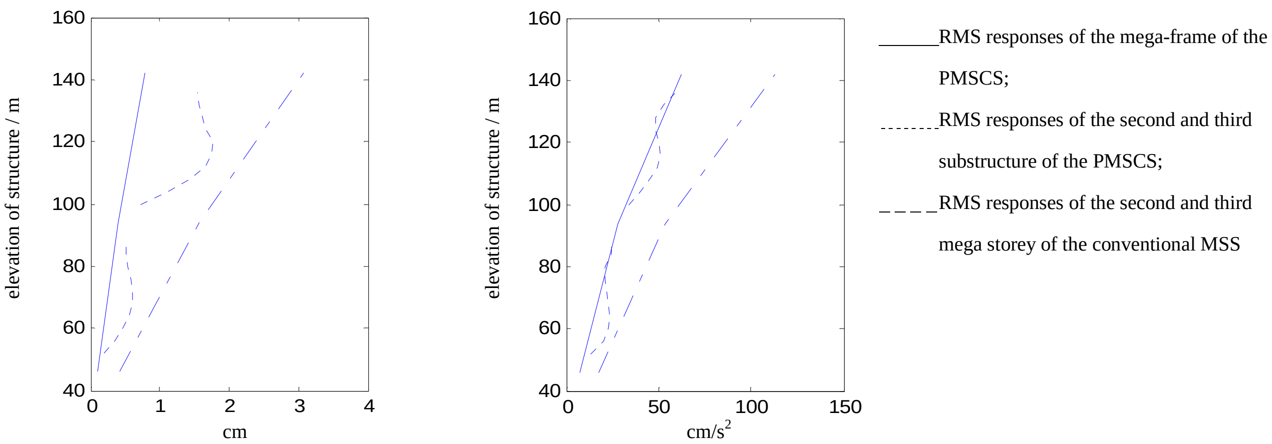
### *3.1. Seismic Response for PMSCS*

Fig. 5 shows the comparison of the *PSD*s for the displacement and acceleration response of the top mega-mass of the PMSCS and the top mass of the conventional *MSS*, when the relative stiffness ratio *RK*=0.17, and the seismic excitation is nonstationary. It shows that the *PSD*s of displacement and acceleration responses at the top mass of the new proposed PMSCS are much smaller than the corresponding responses of MSS. It clearly explained that the release of connections between the mega-frames and substructures make the PMSCS system act as a self-controlled structure is capable of developing very high control energy to control the responses.




(a) The comparison of the displacement response *PSD* (b) The comparison of the acceleration response *PSD*

Figure 5 The comparison of the *PSD*s for the displacement and acceleration response of the top mega-mass of the *PMSCS* and the top mass of the conventional *MSS*, as *RK*=0.17, under nonstationary seismic excitation.

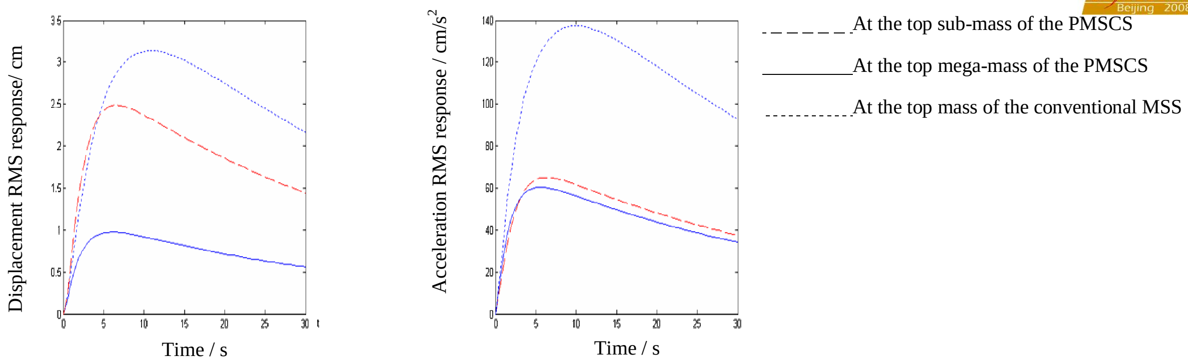



(a) Displacement *RMS* response (b) Acceleration *RMS* response

Figure 6 Distributions of the *RMS* responses along the structural second and third mega storey elevation of the *PMSCS* and the *MSS*, as *RK*=0.13, under nonstationary seismic excitation.

Figs. 6 illustrate the displacement and acceleration root mean square (*RMS*) response distributions of each mass point in the second and third mega-storey of both the PMSCS and conventional MSS. The figures illustrate that the displacement *RMS* responses and acceleration *RMS* responses are significantly reduced in the controlled structure, with the exception of few substructural acceleration *RMS* response. It also shows that the responses are increased from the bottom up of structure, and the maximum appeared at the top mass. So we can investigate the controlling characteristic and controlling effectiveness by the topmost response of structure.

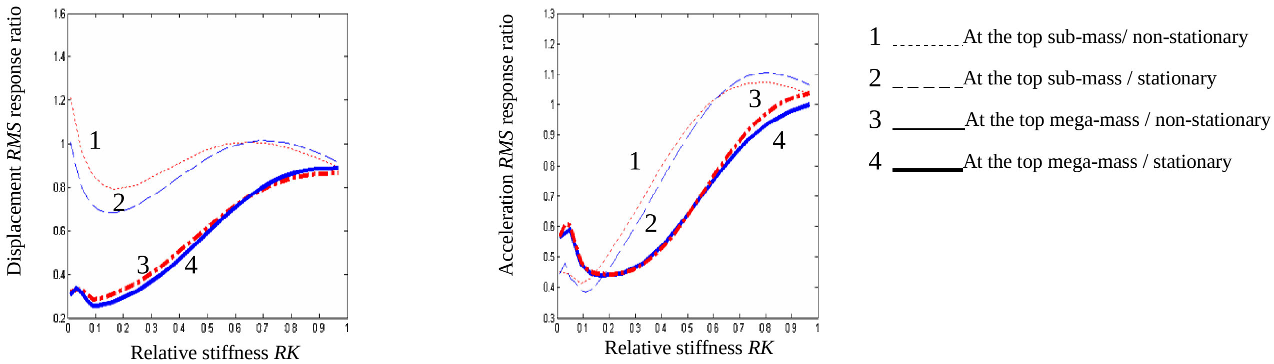
Fig.7 further presents the *RMS* comparison of the displacement and acceleration responses at the top mass of the PMSCS and MSS, we can find that: (i) The *RMS*s responses of displacement and acceleration at the top mega-mass and sub-mass of PMSCS are both decreased obviously compared with those of the conventional MSS, it also reveals the predominance of PMSCS at controlling the structure responses. (ii) The *RMS*s responses of displacement and acceleration at the top mega-mass are smaller than those at the top sub-mass of PMSCS, especially the displacement. Because the mega-frame is composed of mega beams and mega columns, thereby has a strong capability of resisting lateral forces, so the displacement of mega-frame is smaller.




(a) Displacement *RMS* responses (b) Acceleration *RMS* responses

Figure 7 The comparison of *RMS* responses of the two structures, as *RK*=0.17, under nonstationary seismic excitation.

### *3.2 Influence of Structural Stiffness Ratio on the Response Ratio*




(a) The displacement *RMS* response ratio (b) The acceleration *RMS* response ratio

Figure 8 The influence of the structural relative stiffness ratio *RK* on the *RMS* response ratio *RR*

In order to further open out the response controlling effectiveness of PMSCS, the response ratio, *RR*, for the two structures is defined as: *RR*= the *RMS* response of the PMSCS / the *RMS* response of the conventional MSS. Figure 8 presents the RMS response ratio of displacement and acceleration at the top mega-mass and top sub-mass of PMSCS as the relative stiffness ratio *RK*=0~1. In this figure, the dotted lines and dash-dot lines represent the *RMS* response ratios of the top sub-mass and the top mega-mass, under the simulated nonstationary seismic excitation. The dashed lines and solid lines present the *RMS* response ratios at these same locations, corresponding to the simulated stationary ground acceleration. Figure 8 illustrates that:

(1) When *RK*=0.1~0.3, the displacement of mega-frame and substructure is decreased evidently, in this areas there exits an obvious controlling effectiveness for displacement; the acceleration is also decreased, but of substructure the controlling effectiveness is go to the bad comparatively when *RK*=0.2~0.3.

(2) When *RK*≥0.7, the controlling effectiveness of displacement and acceleration responses are all bad, so much as bigger than conventional MSS of substructural acceleration. It indicates that there is taken on definite coupling domino effect between the controlling effectiveness and the relative stiffness ratio of structure.

(3) It can be seen that the controlling effectiveness of PMSCS is influenced greatly by the relative stiffness ratio *RK*. For nonstationary random seismic excitation, when *RK*=0.17, the displacement response ratio *RR* of mega-frame is 31% and of substructure is 81%; the acceleration response ratio *RR* of mega-frame is 45% and of

substructure is 48%.The responses are all decreased to a great extent. So rational distribution of stiffness between mega-frame and substructure should be considered in order to achieving the optimal controlling effectiveness when design the PMSCS.

(4) Fig. 8 also illustrate that the *RMS* response ratios calculated on the basis of the simulated stationary and nonstationary seismic inputs are very nearly the same. This suggests that the stationary random seismic simulation process can be used to approximate closed to the seismic response control effectiveness of the proposed PMSCS in practical engineering design, to reduce the computing time consumedly.

## 4. CONCLUSION

A new structural configuration of the practical passive mega-sub controlled frame is proposed for super tall buildings, which employ the mega-sub structural configuration to form a huge passive controlling structural system. The analytical and numerical studies undertaken in this paper illustrate that the proposed passive mega-sub controlled system configuration acts as a self-controlled structure that is capable of dissipating large amounts of energy induced in the system by seismic ground motions. The displacement and acceleration responses of the proposed PMSCS are very much smaller than those of the conventional building MSS. The response ratio, *RR*, of the displacement response at the top mega-mass and top sub-mass in the example PMSCS investigated in this study were 31% and 81%, respectively; the corresponding values for the acceleration response were 45 % and 48 %. From these results it could be concluded that this structural configuration has a very strong ability in controlling displacement and acceleration responses.

A proposed relative stiffness *RK* region is first presented which are usually used in practice design, While *RK* is in some certain range, such as 0.10~0.30, a remarkable controlling effectiveness can be obtained. However, as *RK* is greater than 0.7, the controlling effectiveness is unacceptable. The optimum region for the relative stiffness ratio, in which the passive mega-sub controlled structure responses approximately reach their optimum (minimum) values, can serve as a very useful tool for structural designers.

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