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Vibration control parameters investigation of the Mega-Sub Controlled Structure System (MSCSS)

Toi Limazie[*1,2], Xun'an Zhang[2a] and Xianjie Wang[2b]

[1] *School of Civil Engineering, Tongji University, Shanghai 200092, China*
[2] *School of Mechanic, Civil and Architectural Engineering, Northwestern Polytechnical University, Xian 710129, China*

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Abstract. Excessive vibrations induced by earthquake excitation and wind load are an obstacle in design and construction of tall and super tall buildings. An innovative vibration control structure system (Mega-Sub Controlled Structure System-MSCSS) was recently proposed to further improve humans comfort and their safeties during natural disasters. Preliminary investigations were performed using a two dimensional equivalent simplified model, composed by 3 mega-stories. In this paper, a more reasonable and realistic scaled model is design to investigate the dynamical characteristics and controlling performances of this structure when subjected to strong earthquake motion. The control parameters of the structure system, such as the modulated sub-structures disposition; the damping coefficient ratio (RC); the stiffness ratio (RD); the mass ratio of the mega-structure and sub-structure (RM) are investigated and their optimal values (matched values) are obtained. The MSCSS is also compared with the so-called Mega-Sub Structure (MSS) regarding their displacement and acceleration responses when subjected to the same load conditions. Through the nonlinear time history analysis, the effectiveness and the feasibility of the proposed mega-sub controlled structure system (MSCSS) is demonstrated in reducing the displacement and acceleration responses and also improving human comfort under earthquake loads.

Keywords: mega-sub controlled structure; vibration control; control effectiveness; structural optimization; modulated sub-structures; viscous damper

1. Introduction

Interested by high-rise structure's functionally efficient and esthetic, and although the important advances made in structural and earthquake engineering which have benefited the analysis, design and construction of civil structures, the safety of these structures still constitute an technical challenge for architects and engineers when subjected to external forces such as earthquakes excitations.

The important issues that constitutes the technical challenge is the problem "of ensuring" the

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*Corresponding author, Ph.D. Candidate, E-mail: mctoyi@hotmail.com
[a] Professor, E-mail: jiaoping@nwpu.edu.cn
[b] Ph.D. candidate, E-mail: xianjiewang@mail.nwpu.edu.cn

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structural integrity of the buildings and the comfort of their contents under wind and earthquake loads. To suffer the integrity and the safety of the structure, building vibration should be controlled and conventional damping devices are used. Therefore, structural characteristics such as large number of devices or additional mass systems attached to the structure would be technically difficult and economically impractical.

Extensive studies have been conducted to improve the structural performance of building under severe external loads implementing vibration control techniques. Among those control techniques, the structural configuration called mega-sub structure (MSS) building which is gaining popularity in the design of tall and super tall buildings; and the new proposed MSCSS configuration designed on the basis of the former structure system.

The MSS structure consists of two major components: a mega-frame which is the main structural frame; and several sub-structures, each containing many stores used for residential and/or commercial purposes. This structure can strongly resist to external loads as wind and earthquake and could also be designed into different ingenious forms to increase the control ability of the structure, such as the new Mega-Sub Controlled Structure System (MSCSS). The new configuration system for controlling dynamic response was first introduced by Feng and Mita in 1995. This model (Feng and Mita 1995, Chai and Feng 1997) is a passive meg-sub controlled system with base-isolated sub-structures. The structure was first modeled by a single-degree-of-freedom system and analyzed under wind load; and later a hybrid mega-sub control concept was proposed in which actuator is added to the passively controlled mega-sub building to further reduce building responses. The wind loads were modeled as a band-limited white noise, the structure was assumed to be of shear type, and the study was limited to the building vibration in the along-wind direction only.

Later, a cantilever beam is used to represent the mega structure to represent tall and supper-tall buildings models where a more realistic wind load model is employed in which the turbulent wind speed is idealized as a non-white stochastic process in time and space.

In 2004, on the basis of this structure, Xun’an Zhang proposed a new controlled structure (MSCSS), in which sub-structures are designed as modulated sub-structures and fixed to the mega-beams structures, and unlike the completely flexible arrangement of the substructures initially proposed by Feng, additional columns are introduced between the mega-frame and the top-level of the substructures (Fig. 3). In past studies (Zhang *et al.*), different controlling mechanisms were examined and compared to the MSS. The results show that MSCSS obviously improves the structure safety under seismic action, reduces structure displacement, velocity and acceleration responses when subjected to random load. However, there still exists some design difficult that need to be addressed before that the proposed structure could be used in practice. At present, the experimental investigation of the mega-sub controlled structure system remained insufficient. This is due to the complexity of the structure and uncertainty of the model′s characteristic will generate expensive cost for experimental studies. Therefore, it is necessary to carry out a full and comprehensive simulation analysis to evaluate the dynamic characteristics of the model before experimental investigation. Based on the finite element software, SAP2000, the influence of the position and number of the modulated sub-structures; the stiffness and mass ratio and other parameters are investigated; with a view to provide a reference for experimental studies and other numerical analysis.

In the present study, a more realistic experimental and scaled 3D model of the MSCSS and MSS are proposed and investigated for further comparison. Notice that these structures are composed by 4 mega stories as presented in Fig. 1 and Fig. 2. To avoid excessive displacements of sub-structures which may cause collision between sub-structures and the mega-structure and also cause concerns of structural safety; and large acceleration responses which could result in damage of buildings contents and residents discomfort, the control parameters of the MSCSS such as the modulated sub-structures disposition, the damping and stiffness ratios, the sub-structures and mega-structure mass ratio are analyzed and the matched parameters are obtained.

2. Vibration control principle of the MSCSS system

As mentioned earlier, MSCSS is an innovative system of vibration control to reduce the dynamic response of tall buildings. Considering the principle of “mega sub-structures configuration” where sub-structures which consist of several floors acts as vibrations absorbers, the response of the structure (mega structure and sub structures) are reduce significantly. This system is cost effective, since it requires no additional masses to control vibrations. The sub-structures have frequency modulation function and are called frequency modulation sub-structures or modulated sub-structures. Notice that the structure is composed by mega-structure and sub-structures. Through this configuration (sub-structures are contained within mega-structure), the new controlling principle is established. First, the vibration energy of the structure due to external loads is transferred into sub-structures which can be achieved by the dynamic characteristics of sub-structures so that the energy flows naturally into sub-structures; then the transferred energy is dissipated in sub-structures. This step can be established by an optimum design of sub-structures and also conventional damping devices could be used for energy dissipation and installed between the mega-structures and sub-structures or between the sub-structures.

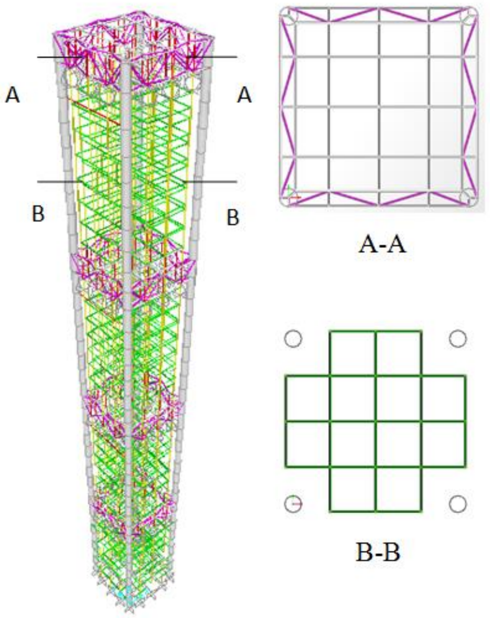

Fig. 1 MSCSS configuration

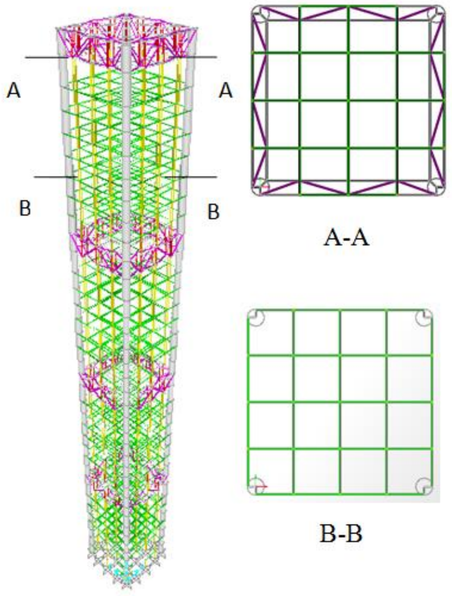

Fig. 2 MSS configuration

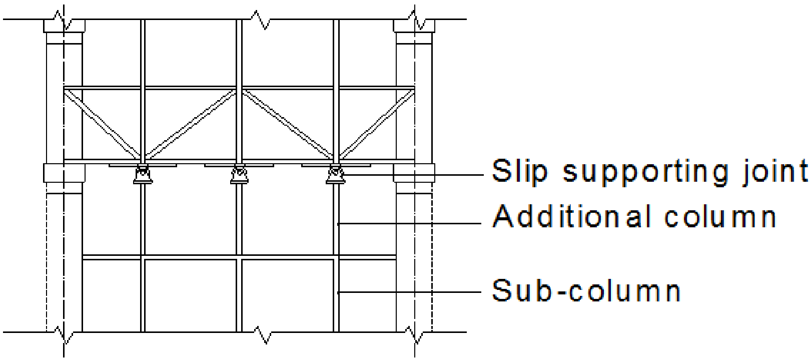

Fig. 3 Additional columns disposition between sub-column and mega-beam

From the control principle, although the MSCSS system is similar to the ideology of TMD system, it is obviously different to the simple combination of the mega-frame structure with TMD control system. The difference between the two controlling systems can be described as follow:

① TMD or MTMD system does not consider the displacement and acceleration response of the frequency modulation lumped mass; while for MSCSS system, reducing the displacement and acceleration responses of sub-structures which are usually used for office or living rooms is an important requirement.

② Sub-structures can be arranged as needed on many mega-stories; and each sub-structure is a multi-degree of freedom system. This structural form is obviously different from the MTMD system.

③ When the MSCSS reaches the elasto-plastic state, its sub-structures will change performance characteristics; while the TMD and MTMD system do not consider the elasto-plastic state of the lumped mass system.

The mechanism of MSCSS is more complex and exist plentiful phenomena which need to be investigated. In addition to the MSCSS structural principle discussed above, others control systems as active, semi-active and hybrid control principle can be very easier implemented on MSCSS configuration (Zhang *et al.* 2009) to further reduce sub-structure responses and improve the comfort and the safety of the MSCSS model when subjected to wind load and strong earthquake excitation. Also, actuators or MR dampers; or actuators combine with viscous dampers can be easily installed between the mega-structure and sub-structure. At this time, implementation of different control process, the mass frequency modulation of the sub-structure still plays an important role.

Therefore, the objective of this study is not only to reduce the vibration of the mega-structure but also to minimize those of the sub-structures to avoid their collision. It is therefore necessary to find matched dynamic parameters of the MSCSS.

3. Analytical model of the structure and dynamic equations

The configuration of a conventional mega sub-controlled structure system is illustrated in Fig. 1, where the main structure is the mega frame, composed of mega columns and mega beams with

Table 1 structures members sections characteristics

Members	Sections	A(mm^2)	I(mm^4)
Mega-column	◎	188.4956	21300
Sub-column	○	15.9043	20.1289
Sub-beam	○	12.5664	12.5664
Additional column	○	15.9043	20.1289
Orthogonal braces	○	12.5664	12.5664

several sub-structures attached. In this study, the mega beam (here mega floor) is composed by an ensemble of beams, columns and orthogonal braces. These proposed sub-structures should enable that the interaction between the mega frame and substructures can be used to control or suppress the building vibrations. Sub-structures are designed as modulated sub-structures and fixed to the mega-beams structures, and unlike the completely flexible arrangement of the substructures initially proposed by Feng, additional columns are introduced between the mega-frame and the top-level of the sub-structures. And slip supporting hinge joint on the top of additional column is set to relax horizontal constrains between additional columns and mega-beams to improve mechanical behaviors of additional columns as shown in Fig. 3. Two viscous dampers are installed at the top of the first, the second and the third sub-structure (the 2nd, 3rd and 4th mega stories).

The structure design in this paper is a steel structure model composed to 4 mega stories and has 2.95 m of high and 0.34 m of large. For further comparisons, the two buildings have the same amount of total mass and same structural members as presented in Table 1, and also have the same damping characteristics.

The analytical model of the mega sub-controlled structure is obtain by considering that the structure is discredited as a multi-degree-of –freedom system (MDOF). Also bending is the dominant vibration mode for the mega-structure, while shear is the governing mode for the sub-structures; since the sub-structures are usually not slender.

Supposing that the structure has n mega-floors and n_s sub-structures, each of which consists of n_z floors, the total number of degree of freedom of this structure is $N = n + n_s \, x \, n_z$. Therefore, the dynamic equation of the system under seismic loads is expressed by

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = -MI\ddot{X}_g(t) \tag{1}$$

Where $X = [x_P^T, x_1^T, x_2^T, \ldots, x_{ni}^T]^T$ is the deformation vector of the building. x_p^T and x_i^T ($I = 1,2,\ldots.n_i$) are the deformation vectors of the mega-structure and the i^{th} sub-structure respectively; M is the mass vector; X_g is the random seismic acceleration excitation.

$$M = diag\left[M_P, M_1, M_2, ..M_i ..., M_{ns}\right] \tag{2}$$

Where M_p is the $n \times n$ diagonal mass matrix of the mega-structure, and M_i, $i = 1, 2, \ldots, n_s$ is the $n_z \times n_z$ diagonal mass matrix of the i^{th} sub-structure.

The stiffness matrix K is expressed as

$$K = \begin{bmatrix} K_P + K_{s,diag} & K_c \\ K_c^T & K_s \end{bmatrix}, \qquad (3)$$
$$K_s = diag\left\lfloor K_{s,1}, K_{s,2}, ...K_{s,i}, ..., K_{s,ns} \right\rfloor$$

Where K_p is the $n \times n$ stiffness matrix of the mega structure; $K_{s,i}$; $i = 1, 2, ..., n_s$ is the $n_z \times n_z$ stiffness matrix of the i^{th} sub-structure.

The damping matrix is obtained as follow

$$C = \begin{bmatrix} C_P + C_{s,diag} & C_c \\ C_c^T & C_s \end{bmatrix}, \qquad (4)$$
$$C_s = diag\left\lfloor C_{s,1}, C_{s,2}, ..., C_{s,i}, ..., C_{s,ns} \right\rfloor$$

Where C_p is the $n \times n$ damping matrix of the mega structure, and $C_{s,i}$, $i = 1, 2, .., n_s$ is the $n_z \times n_z$ damping matrix of the i^{th} sub-structure. The $n \times n_s n_z$ matrix C_c is the coupling damping matrix between the mega-structure and sub-structures.

4. Optimal design of sub-structures of the MSCSS model

The MSCSS is designed through the optimization of the dynamic characteristics of the system which is composed of mega-structure and sub-structures to minimize vibrations in the building. As depicted on Fig. 1 above, the MSCSS is composed by 3 "modulated sub-structures" and 1(one) "attached sub-structure". The aim of the optimization in this section is to find the optimal arrangement of these sub-structures within the mega-structure so that the vibration responses of the structure system can be minimized. The optimal values of the dynamic parameters of the optimal model in the same way will be examined later. For this purpose, 5 models have been designed and investigated; regarding the displacement and acceleration responses of the structures. The different models are describe as follow and shown in Fig. 4.

- Model 1 is composed by three (3) "modulated sub-structures" and one "attached sub-structure" at the bottom.
- Model 2 consists of one "modulated sub-structure" at the top of the building and 3 "attached sub-structures".
- Model 3: two "modulated sub-structures" at the top and two "attached sub-structures" at the bottom.
- Model 4: two "attached sub-structures" at the bottom and one "modulated sub-structure" at the top of the building with the 3rd mega-floor empty.
- Model 5 constituted by 3 "modulated sub-structures" and 1 "attached sub-structure" at the top of the building.

It was shown during the first evaluations that it is very difficult and almost impossible to find an optimal model which can achieve the minimum displacement of the mega structure and minimum acceleration of the sub-structure simultaneously, at the top and bottom of the structure. It is for this raison that two viscous dampers are added at the top floor of each modulated sub-structures.

It notes that to reasonably compare the performance of these buildings, the same parameters of the viscous damper are adopted for all models in numerical analysis.

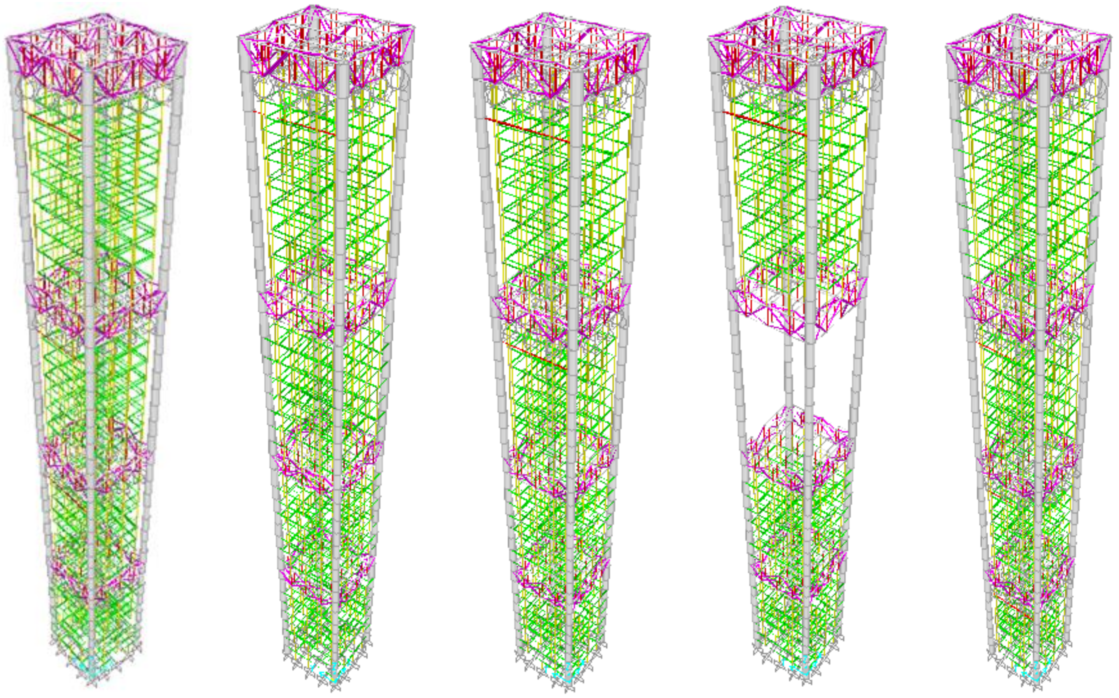
(a) (b) (c) (d) (e)

Fig. 4 Different models of MSCS (a) model 1, (b) model 2, (c) model 3, (d) model 4 and (e) model 5

Therefore, in the present study, nonlinear finite element analysis method is used to obtain the target responses of the buildings. Simulating these buildings, subjected to El-CENTRO wave, the peak target responses values can be obtained for different buildings models. Also the root mean square values (RMS) can be computed. The peak ground acceleration is set to 0.4 g and the analysis results are plotted in Figs. 5-6. Here, the maximum and RMS values of acceleration and displacement are chosen to be the target responses and are compared to those of the traditional mega sub-structure (MSS). The model which produces the minimum target responses is regarded as the optimal designed model and is use for further investigations. From figures (Figs. 5-6), it can be seen that the vibration responses of the model 1, model 3 and model 5 are significantly reduced. It is also found that the displacement and acceleration of the bottom and the top of the model 1 are significantly reduced, which is not achieve by the MSS model. It can be remarked that more the building (MSS) is slender, more is the response of this structure; this obviously affect the safety and comfort of occupants. The Fig. 5 illustrates more clearly the influence of sub-structures, especially at the top of the building. It can be seen that the acceleration of the model 2 (one modulated sub-structure at the top of the building) is obviously reduced. The results depicted in figures (Figs. 5-6) shows that minimum responses are obtained when the building is composed by 3 modulated sub-structures and one attached sub-structure. However, it still difficult to obtain minimum acceleration and displacement responses at the top and bottom of the building simultaneously (model 5). The model 1 which achieve better to this requirement is obtain as the optimal design model for more investigations. Notice that the break on the curve 4 (model 4) is due to the gap in the structure at the 3rd mega-floor.

5. Effect of dynamic parameters of MSCSS on the controlling effectiveness

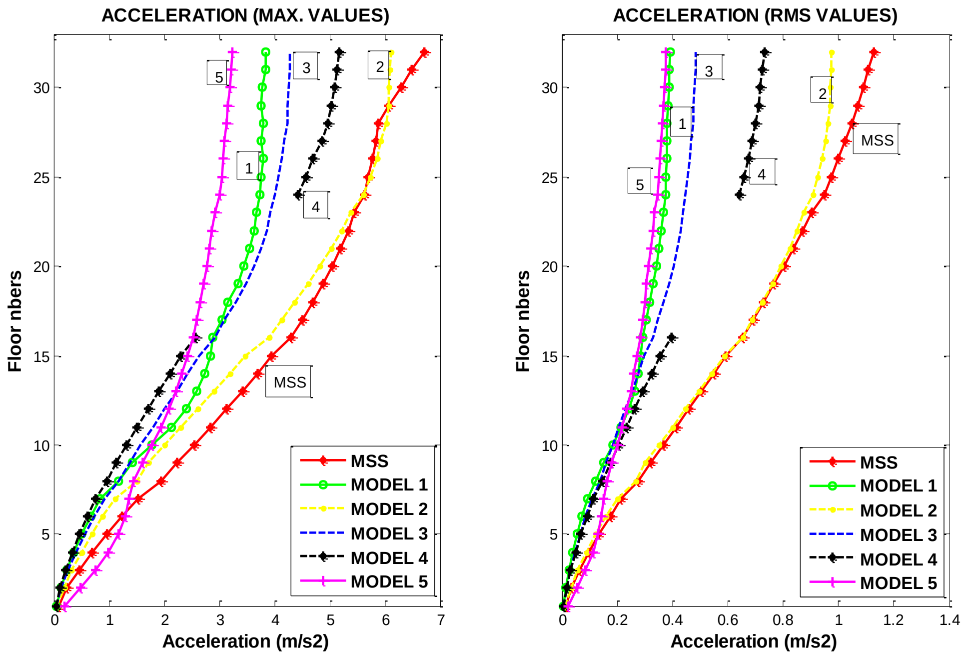

Fig. 5 Floors acceleration responses for different disposition of sub-structures

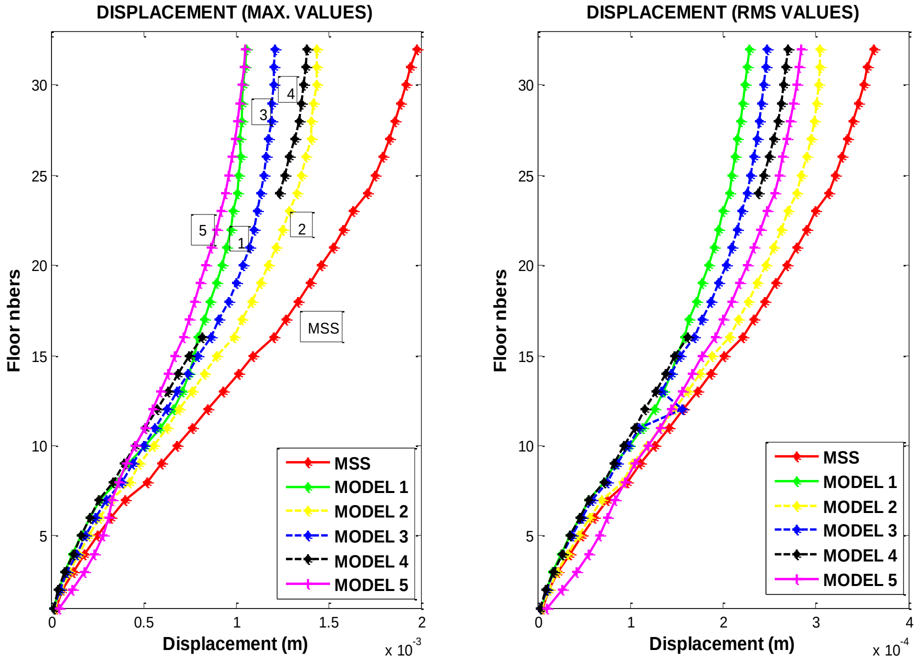

Fig. 6 Floors displacement responses for different disposition of sub-structures

The mega-sub controlled structure system which is design through the principle of “modulated sub-structure” presents a complex controlling mechanism and need to be design accordantly to achieve the goal. In order to investigate the effectiveness of the mega-sub controlling structure system under strong earthquake motions, some important parameters are investigated. The sub-structural stiffness ratio (RD), damping ration (RC) and the sub-structure and mega-structure masses ratio (RM) are studied and the values which produce the minimum target responses are set as optimal structural parameters of the building.

The model 1 of the MSCSS is use in this part to examine the influence of these 3 parameters on the effectiveness of the building. The total mass of the MSCSS building is M_t = 39.53 kg and the fundamental period T_1 = 0.089s. For the MSS the total mass and period are 40.789 kg and 0.094 s, respectively. The conventional mega-sub structure (MSS) and the mega-sub controlled structure system (MSCSS) have the same damping characteristics, resulting in a 2% damping ratio (typical value for steel structures), for all vibration modes.

5.1 Sub-structural stiffness ratio (RD) and mass ratio (RM) effects

In the mega-sub controlled structure, the damping ratio and the sub-structure stiffness ratio play an important role. They should be design to be the optimal values in order to minimize the target responses of the building when subjected to seismic excitations.

To examine the sub-structural stiffness change effect on the effectiveness, the sub-structural stiffness ratio RD is defined and expressed as

$$RD = \frac{K_{sub}}{K_{mega} \times N_s} \tag{5}$$

Wherein K_{mega} is the mega-structure stiffness and is expressed as

$$K_{mega} = \frac{3EI}{H_{meg}^3} \tag{6}$$

E is the elastic modulus of steel and I the moment of inertia of the mega-column. H_{mega} is high of the structure. N_s is the floor’s number in one sub-structure; K_{sub} is the sub-structure inter-story stiffness and expressed as

$$K_{sub} = 0.142 \times 10^6 \times E \times I_{sub} \tag{7}$$

The relative mass ratio (RM) between the mega frame is also examined and defined as follow by Eq. (8)

$$RM = \frac{\sum M_{sub}}{\sum M_{mega}} \tag{8}$$

Wherein, M_{sub} is the total mass of the sub-structures and M_{mega} is the total mass of the mega-frame.

The target responses of the MSCSS under strong earthquake excitation are computed and shown in Fig. 7, with different values of stiffness ratio RD.

It is clearly shown in these figures that the target responses of the MSCSS building will be

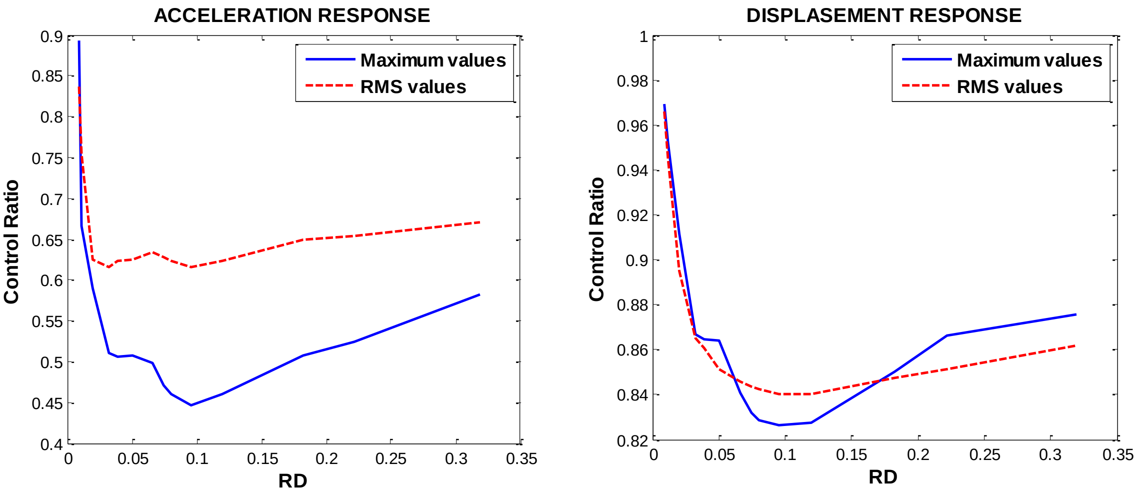

Fig. 7 Influence of stiffness ratio on the controlling performance

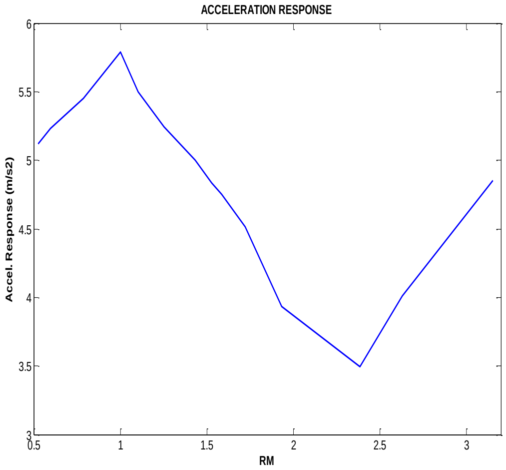

Fig. 8 Mass ratio influence on acceleration response of the MSCSS

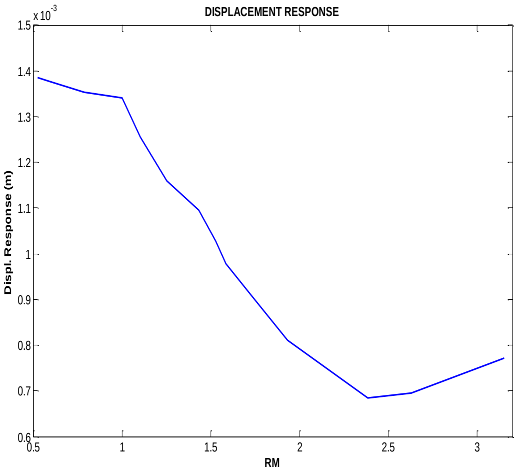

Fig. 9 Mass ratio influence on displacement response of the MSCSS

consequently altered as the stiffness ratio vary and different controlling mechanisms are observed.

It can be seen that within certain rang of values of RD, the MSCSS building does not exhibit the expected controlling effectiveness. It is shown that the maximums target responses (acceleration and displacement) of the MSCSS building are obtained when the stiffness ratio is evaluated between 0.03 ~ 0.12. A very important slope is observed when RD < 0.03; the structure depicts a sudden drop of the controlling effectiveness. While for RD > 0.15, the curve will rise spontaneously and then tend to a relatively stable point (RD = 0.32). The displacement and acceleration responses of the structure are decrease evidently (RD = 0.15 ~ 0.32).

Figs. 8 and 9 further show the influence of the relative mass ratio between the mega structure and the sub-structures on dynamic responses of MSCSS. The figures present the acceleration and displacement responses at the top floor of the mega structure with mass ratio variation. It is found that the controlling effectiveness will be improved when the mass ratio RM increases. It is also found that when the mega frame’s mass is equal to that of the total mass of sub-structures, the acceleration responses of the structure increases and the maximum response is reached at this point.

For RM = 1.00 ~ 2.4, both the acceleration and displacement responses will steeply decrease and reach the minimum values for RM = 2.38. While for certain value of mass ratio (RM > 2.4), the vibration responses will spontaneously increase. The variations of controlling performances of the MSCSS with different RD and RM once show the complexity of this new controlling structure system. It is demonstrated that for RM = 2.38 and RD = 0.15 ~ 0.32, the vibration responses of the structure can be reduced obviously, as expected.

5.2 Investigation of damping ratio effect

Viscous dampers are an important part of the mega-sub controlled structure system and their parameters changes have great influence on structural parameters. The damping ratio RC is also investigated in this research. The RC is defined by Eq. (9) as follow

$$RC = \frac{n \times C}{50.787} \tag{9}$$

Where *n* is the number of dampers per sub-structure and C the damping coefficient of the viscous damper. 50.787 is sub-structure inter-story damping value.

MSCSS is analyzed with different values of damping ratio and damper’s stiffness coefficient (K) and the controlling performances are compared to those of the traditional mega-sub structure (MSS). Figs. 10 and 11 present the results of acceleration and displacement control ratios at the top floor of the mega-frame, respectively, for RM = 0.6 and RD = 0.03. It clearly demonstrates the impact of dampers on this structure system. Notice that during the simulation, Maxwell model of the viscous damper were considered. It can be seen from these figures that for small values of K and RC, the controlling performance expected cannot be reached; the target responses of the MSCSS are much greater than those of the MSS. Also for K < 8.0E+6, the acceleration and displacement responses are almost unchangeable for any value of RC. The controlling performances of the MSCSS will increase and reach the maximum for RC = 3.0E+5 ~ 4.0E+6. The control ratio will then slightly decrease for RC greater than this range of values. It’s shown that the controlling effectiveness can reaches 90% for the acceleration and displacement at the top floor of the mega-structure when two (2) viscous dampers are installed at the top floor of each modulated sub-structures. This demonstrates that the MSCSS can effectively absorb or reduce dynamical responses of the building and also perfectly combine the control theory of sub-structures self-controlled principle with energy dissipation by damping devices.

6. Conclusions

Through the time history analysis of the seismic response of the mega-sub controlled structure system (MSCSS), the performances of the building have been demonstrated. The optimal values of control parameters have been also generated. It is found that (1) the proposed MSCSS can effectively reduce target responses (such as acceleration and displacement) on the building much

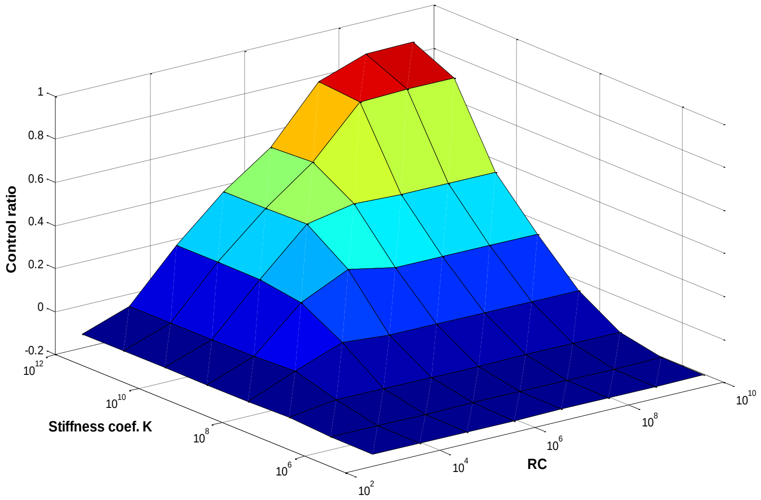

Fig. 10 Displacement response of the MSCSS for RM = 0.6 and RD = 0.03

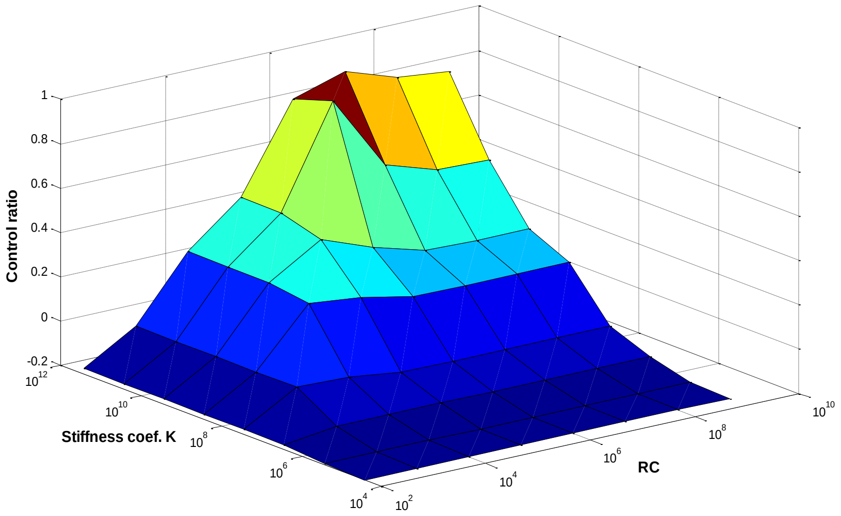

Fig. 11 Acceleration response of the MSCSS for RM = 0.6 and RD = 0.03

more than the conventional mega-sub structure (MSS), both for the mega-frame and sub-structures; (2) the optimum structural parameters have a major or great influence on control effectiveness; (3) the proposed control method is feasible and practical for frame buildings since these parameters can be achieved easily.

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