Study on Damper Distribution of the Mega-Sub Controlled Structure System Under Earthquake Actions

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Abstract. An innovative vibration control structure system (Mega-Sub Controlled Structure System-MSCSS) is proposed and investigated based on the structural response control principle and structural construction theory. Unlike the conventional mega-frame structures (MFS), functional elements were applied in MSCSS so as to achieve effective structural response control. The focus of this study is to investigate the damper distribution of MSCSS under seismic actions. And the seismic energy analysis method was adopted to study elastoplastic properties of MSCSS. Finally, it was proved that MSCSS had better seismic performance by analyzing displacement response and energy dissipation of the structure. In addition, the distribution of dampers was further discussed for the purpose of achieving the best control effect.

1. Introduction
The mega-sub controlled structure was first introduced by Feng and Mita (1995)[1] for controlling tall buildings responses when subjected to severe external loads, such as wind and earthquake, which consists of two major components, namely a mega-frame serving as the main structural component, and several sub-structures with each containing many stories for residential purposes. The analysis model was relatively simple, since the main structure and the substructures were respectively simplified to one degree of freedom. Subsequently, by improving the configuration, Winson Chai and Maria Q. Feng (1997)[2] studied the dynamic response of the structure to random wind load excitations. After that, Lan (2002)[3] proposed a multi-function mega-substructure in the system, which is controlled by a combination of TMD effect and base isolated substructures. However, it is worth noting that, in order to apply the above new structural systems in engineering practice, there are many design difficulties that need to be overcome. At the beginning of 2004, an improved practical MSCSS was designed by Xuan’an Zhang [4][5] with reference to the construction of mega-frame structure (MFS), e.g., the Bank of China at Hong Kong and Tokyo City Hall at Japan, in which sub-structures were designed as modulated sub-structures and fixed to the mega-beams structures,
unlike the completely flexible arrangement of the substructures initially proposed by Feng, and dampers were installed between the main structure and substructures. It was found that the improved MSCSS could provide a large amount of energy for vibration control and, therefore, was very effective in reducing structural displacement and acceleration response.

2. Elastic-plastic analysis of MSCSS

2.1. FE model of MSCSS
To research on the lumped mass model of MSCSS by the complex modal analysis method can only analyze the structural deformation in the elastic state. Thus, the finite element method model of MSCSS is needed to discuss the structural nonlinear response when the structure steps into the plastic state. Based on the concept of mega-sub controlled structural system(MSCSS), the completed architectural form of mega frame structures(MFS), and the equivalent simplified model of MSCSS proposed by reference. The plane finite element model of MSCSS is created, as shown in Figure 1-a. Meanwhile, the model of mega frame structure(MFS) is shown in Figure 1-b, which has the same section size with MSCSS.

Figure 1. The finite element model

2.2. Different damper distribution of MSCSS
Five different damper distributions in the MSCSS are given below, as shown in Figure 2.

Scheme1:
Two layers of dampers were installed for each substructure in the layers with the ultimate story drift (layer 3) and the maximum displacement (layer 7), respectively;

Scheme2:
Two layers of dampers were installed for each substructure in the layers with the ultimate story drift (layer 2 and layer 4).

Scheme3:
Two layers of dampers were installed for each substructure in the layers with the maximum displacement (layer 5 and layer 7).

Scheme4:
Since the 1st and 3rd substructures exhibit either too weak or too strong acceleration control effect the 1st substructure is equipped with three layers of dampers, which are respectively installed in the
2nd, 4th, and 7th layer. The 2nd substructure employs the same distribution as scheme 1. The 3rd substructure is equipped with one layer of dampers in the 7th layer.

Scheme5:
Similar to Scheme4, the dampers of the 1st substructure are installed in the 1st, 3rd and 5th layer. The dampers of the 2nd substructure are decorated in the 2nd and 4th layer, while and the 3rd substructure are equipped in the 3rd layer.

![Diagram of damper layout schemes](image)

Figure 2. The layout schemes of the damper in the MSCSS

2.3 Structural response and energy dissipation of MSCSS
Given the fact that MSCSS is less sensitive to the seismic wave, and the structure plastic development process also needs to be investigated, El.centro wave is adopted to apply on the structure with a peak acceleration of 1200gal. Table1 and Table2 present the displacement control rate and the acceleration control rate of each scheme. Figure 3 and Figure 4 display the maximal story drift of the 1st and the 3rd substructure, respectively. It is manifested that the control effect of structural responses are significant different between different distribution schemes, nevertheless, the overall response level is much lower than that of MFS. It is worth noting that the acceleration control rate of the 1st substructure does not improve obviously among different schemes, indicating that the damper distribution of 2nd and 3rd substructures have little influence on the control effect of the 1st substructure. Further, the dampers in Scheme 2 and 5 is distributed from the perspective of controlling story drift, but the results showed poor control effect of the story drift. The reason is that the work of the dampers mainly depends on the reciprocating motion between the mega and sub structures, small reciprocating motion would surely induce poor work efficiency, thereby influencing control effect of the story drift.

| Vertex position | MFS displacement | Scheme1 control rate | Scheme2 control rate | Scheme3 control rate | Scheme4 control rate | Scheme5 control rate |
|-----------------|-----------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Substructure 1  | 0.4760          | 12.12%              | -1.99%              | 8.22%               | 10.27%              | 2.59%               |
| Substructure 2  | 0.8451          | 27.11%              | 29.61%              | 24.22%              | 24.99%              | 29.28%              |
| Substructure 3  | 1.0426          | 3.46%               | 7.37%               | 1.44%               | 0.85%               | 5.14%               |
| Megastructure   | 1.0632          | 6.68%               | 10.11%              | 4.81%               | 7.11%               | 10.15%              |
Table 2. The control rate of acceleration of MSCSS in different damper layout schemes

| Vertex position | MFS acceleration | Scheme1 control rate | Scheme2 control rate | Scheme3 control rate | Scheme4 control rate | Scheme5 control rate |
|-----------------|------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Substructure 1  | 17.2511          | -21.75%              | -9.34%               | -33.55%              | -26.833%             | -23.31%              |
| Substructure 2  | 15.2673          | 4.57%                | -10.33%              | 3.56%                | 5.21%                | 4.27%                |
| Substructure 3  | 18.36856         | 9.34%                | 8.07%                | 10.13%               | 7.72%                | 7.16%                |
| Megastructure   | 19.7470          | 24.14%               | 20.67%               | 26.03%               | 25.36%               | 21.28%               |

Table 3. The energy analysis results of MSCSS in different damper layout schemes (kN⋅m)

| Energy                | MFS   | Scheme1 | Scheme2 | Scheme3 | Scheme4 | Scheme5 |
|-----------------------|-------|---------|---------|---------|---------|---------|
| Total input energy $E_{in}$ | 5115.4 | 4506.2  | 4321.5  | 4587.2  | 4554.4  | 4489.5  |
| Energy dissipation of dampers $E_d$ | 0.0000 | 2239.0  | 1662.2  | 2274.0  | 2235.5  | 1843.8  |
| Kinetic energy $E_k$ | 176.60 | 88.486  | 50.235  | 101.29  | 94.523  | 64762   |
| Damping energy dissipation $E_c$ | 4690.1 | 2175.4  | 2501.6  | 2134.3  | 2148.8  | 2406.3  |
| Damping energy dissipation ratio | 91.42% | 47.43%  | 56.41%  | 46.54%  | 47.10%  | 53.63%  |
| Elastic strain energy $E_k$ | 189.83 | 53.529  | 153.421 | 38.813  | 48.936  | 125.91  |
| Hysteretic energy dissipation $E_h$ | 137.59 | 59.402  | 80.95  | 39.997  | 35.903  | 54.844  |
| Hysteretic energy | 2.57%  | 1.28%   | 1.72%   | 0.76%   | 0.78%   | 1.22%   |
The process of the energy analysis for the structure can be briefly introduced as follows:

\[ \int_0^t \dddot{x}^T M \dddot{x} dt + \int_0^t \dddot{x}^T C \dddot{x} dt + \int_0^t \dddot{x}^T K x dt = -\int_0^t \dddot{x}^T M \dddot{\lambda}_y(t) dt \]  

(1)

Where, each term in the left side of the equation can be expressed as kinetic energy, damping dissipation energy, and deformation energy of the structural system, respectively. Represented by symbols, they are \( E_v \), \( E_c \), and \( E_y \), in turn. Besides, \( E_y \) contains elastic strain energy \( E_k \) and hysteretic dissipation energy \( E_h \). The term in the right side of the equation is the total input energy \( E \) in the earthquake. That is, at any time, the total input energy of the structure system is equal to the sum of the other energy.

\[ E_v + E_c + E_y = E_v + E_c + E_k + E_h = E \]  

(2)

For the structure with viscous dampers, the equations are converted to:

\[ M \dddot{x} + C \dddot{x} + K x + f_d = -M \dddot{\lambda}_y(t) \]  

(3)

\[ E_v + E_c + E_k + E_h + E_d = E \]  

(4)

Where, \( f_d \) is the column vector of the viscous damper control force; \( E_d \) is energy dissipation of the viscous dampers, it can be calculated by:

\[ E_d = \int_0^t \dddot{x}^T f_d dt \]  

(5)

Subsequently, Eq(20) is converted to the incremental forms. Finally, the analytical results of the structure elastoplastic energy are obtained. Then, the energy analysis for the five schemes is carried out, the results are shown in Table 3. It could be acknowledged from the above tables that: (1) the total input energy of every scheme is analogous to each other, with Scheme 1 being maximum and Scheme 2 being minimum; (2) the work efficiency of dampers varies in different schemes. The energy dissipation in Scheme 2 is minimal, while scheme 3 is maximal. Comparison of the total input energy, the gap between Scheme 2 and Scheme 3 is larger. (3) The structural dissipating hysteretic energy is generally consistent with the plastic development results. The greater the hysteretic energy is, the degree of the plastic development is higher; (4) The dampers in Scheme 2 and 3 are respectively decorated in accordance with the maximum of story drift and displacement. It could be observed that the degree of the plastic development is small for Scheme 3.

### 3. Conclusions

Based on the structural response control principle and structural construction theory, MSCSS employs functional elements (sub-structure) of the structure itself to achieve structural response control which is a new structural design principle and response control theory and extensively accepted by researchers in recent years. The results indicated that MSCSS had better seismic performance than MFS and damper installed in layer 5 and layer 7 of every substructure could gain satisfying control effects.

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