International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:5, No:12, 2011

The Nonlinear Dynamic Elasto-Plastic Analysis for Evaluating the Controlling Effectiveness and Failure Mechanism of the MSCSS

Toi Limazie, Xun'an Zhang and Xianjie Wang

Abstract**—**This paper focuses on the Mega-Sub Controlled Structure Systems (MSCSS) performances and characteristics regarding the new control principle contained in MSCSS subjected to strong earthquake excitations. The adopted control scheme consists of modulated sub-structures where the control action is achieved by viscous dampers and sub-structure own configuration. The elastic-plastic time history analysis under severe earthquake excitation is analyzed base on the Finite Element Analysis Method (FEAM), and some comparison results are also given in this paper. The result shows that the MSCSS systems can remarkably reduce vibrations effects more than the mega-sub structure (MSS). The study illustrates that the improved MSCSS presents good seismic resistance ability even at 1.2g and can absorb seismic energy in the structure, thus imply that structural members cross section can be reduce and achieve to good economic characteristics. Furthermore, the elasto-plastic analysis demonstrates that the MSCSS is accurate enough regarding international building evaluation and design codes. This paper also shows that the elasto-plastic dynamic analysis method is a reasonable and reliable analysis method for structures subjected to strong earthquake excitations and that the computed results are more precise.

Keywords**—**controlling effectiveness, Elasto-plastic dynamic analysis, Mega-Sub Controlled Structure, Plastic hinge pattern.

I. Introduction

In recent years, Engineers and Architectures have been interested in the study of theory and practical application based on structural earthquake performance. Important advances although made in materials, geotechnical and structural engineering have benefited the analysis, design and construction of civil structures such as tall buildings and super-tall buildings to improve the characteristics and performances of these structures under natural disasters such as wind loads and earthquake excitations, the safety of these structures and their contents as well as the comfort of occupants, under these external forces remains still a significant engineering concern.

New-style and high performance structure, the Mega-Sub Structure (MSS), has been used in construction of many tall buildings and super-tall buildings such as the Bank of China at Hong Kong and Tokyo City Hall at Japan. This 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. The MSS 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) studied in this paper. A new configuration for controlling dynamic response of MSS was first introduced by Feng and Mita in 1995. This structure takes advantage of the so-called Mega-sub Structure configuration which is gaining popularity in design and construction of tall and super tall building. The proposed model [1], [2] is a passive meg-sub controlled system with base-isolated sub-structures. In their studies, 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 response. 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, a new controlled structure (MSCSS) was designed by Xun'an Zhang, 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.1 and 2). MSCSS structure is designed based on the combination of the control principle of structural response and structural configuration principle employing the structure its own functional element such as sub-structure to form structural response control systems. The structural response control through the structure itself functional elements (sub-structures) is a new control structural design principle and response control theory realized in recent years by researchers. In earlier studies [3]-[4]-[5], structural parameters and controlling mechanism are examined and compared to the MSS. The results show that MSCSS obviously improves the structure's safety under seismic action, reduces displacement, velocity and acceleration responses when subjected to random load; and also improves the comfort of the structure. However notice that these studies were performed under elastic state, the elasto-plastic was not

Toi Limazie is with the School of Mechanic, Civil and Architectural Engineering, Northwestern Polytechnical University, Xi'an 710129, People's Republic of China (phone: +86-029-15191436270; e-mail: mctoyi@hotmail.com).

Prof. Xun'an Zhang is with the School of Mechanic, Civil and Architectural Engineering, Northwestern Polytechnical University, Xi'an 710129, People's Republic of China (e-mail: jiaoping@nwpu.edu.cn)

Xianjie Wang is with the School of Mechanic, Civil and Architectural Engineering, Northwestern Polytechnical University, Xi'an 710129, People's Republic of China (e-mail: xianjiewang@mail.nwpu.edu.cn).

considered until now. To confirm theses performances, elasto-plastic analysis need to be investigated under rare earthquake and strong wind loads excitations and evaluate the performances and failure mechanism of this structure.

In this paper, the aim of the research is to carry out the dynamic performances of the MSCSS systems under rare earthquake using the elasto-plastic time history analysis method. The elasto-plastic dynamic analysis method not only gets accurate structure internal forces and deformations, but also estimates the yielding mechanism, the weak positions and the destruction form of the structure when subjected to severe earthquake excitation. In this study the used method is to get elastic-plastic time history response of the structure under earthquake action through step-by-step integration of the dynamic equation, using SAP2000 software. The elasto-plastic time history analysis of Mega-Sub Structure (MSS) and the new MSCSS under severe earthquake is performed and analyzed; and finally comparison studies are given.

II. Structural Configuration and Response Control Principle of MSCSS

As shown in fig.1and fig.2 of the MSCSS configuration, the mega-frame (mega-columns and mega-beams), viscous dampers, and sub-structures (the 2nd and 3rd sub-structure of the figure) forms the fundamental elements of modulated sub-structural control system. These sub-structures have frequency modulation function and are called frequency modulation sub-structures. To overcome the beam large span design problems, additional columns are designed at the top floor of sub-structures as mentioned before. 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.

From the control principle, although MSCSS system is similar to the ideology of TMD system, it is obviously different to the simple superposition 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 above points illustrates that MSCSS constitutes a new form of controlling principle which is obviously different to TMD or MTMD control system and the mechanism of MSCSS is more complex and exist plentiful phenomena which is not relisted and need to be investigated. In addition to the MSCSS structural principle discussed above and its response control (passive) feature, it still very easy to implement others control systems as active, semi-active and hybrid control principle on MSCSS configuration [5]. Actuators or MR dampers; or actuators combine with viscous dampers can be easily installed between the mega-structure and sub-structure. At this time of implementation of different control process, the mass frequency modulation of the sub-structure still plays an important role. Also according to the needs of the control characteristics, friction dampers can be arranged into MSCSS sub-structures [6]. 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.

In this paper, a more realistic analytical model of this structure is proposed, and a practical steel mega-sub controlled frame is investigated.

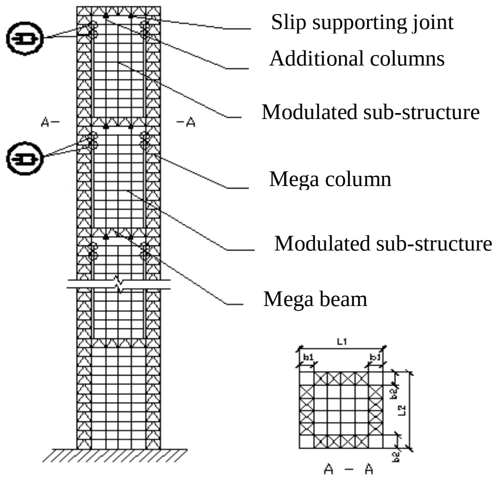
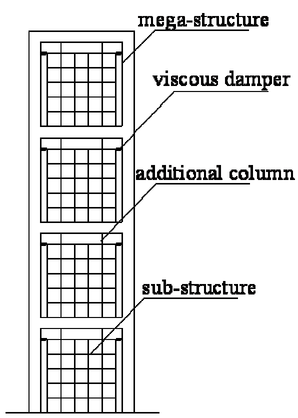


Fig.1 Finite element model of the MSCSS



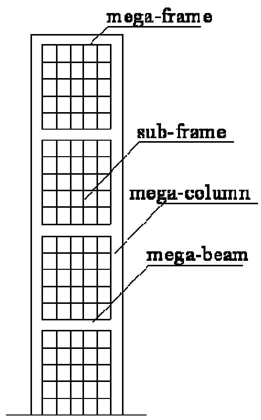


Fig. 2 MSCSS configuration Fig. 3 MSS configuration

III. FEM Model of MSCSS and Its Equivalent Simplified Model

The mega-sub controlled structure is a large and complex form of new high-rise structure system. From fig.1 the equivalent finite element model can be established, where mega-beams and mega-columns are latticed structures. Therefore, there will be a large number of design finite elements, unfavorable to the computation process of the response and control mechanism of the structure. Because of the complicated form of the structure, the latticed mega component, floors disposition concept are obviously different to the conventional structure system. Therefore, to further improve the finite element model of the structure, in the sense of the mechanical behavior of the structure it is need to analyzed the equivalent simplified model of latticed mega-beams and mega-columns using the following principle [8].

Mega-columns are considered as space continuum system and using the mathematical model of continuum transformation, equivalent stiffness is developed by (1):

$$EA_{cei} = E\sum_{i=1}^{4} A_{ci} \tag{1}$$

where A_{ci} is the cross sectional area of the shear column and A_{cei} the cross sectional area of the equivalent mega-column. The equivalent bending stiffness is obtained by (2):

$$EI_{cei} = E\sum_{i=1}^{4} A_{ci} (\frac{a}{2})^2 + EI_c \tag{2}$$

I_{cei} is the equivalent moment of inertia and I_c the moment of inertia of the original shear column.

For mega-beams, the desires equivalent beam stiffness is the unified stiffness of the whole beam root. The moment of inertia of the mega beam can be calculated as:

$$I_{be} = \sum_{i=1}^{4} A_i (\frac{h_i}{2})^2 \tag{3}$$

and the equivalent bending stiffness can be obtained by EI_{be} where E is the elastic modulus of steel. The equivalent transformation process of the beam and column are shown in fig.4. Notice that the original mega-beams are composed by 4 H steel rods connected and mega-columns are also composed by 4 ☐ rods elements connected to form a space truss structure as shown in figure.

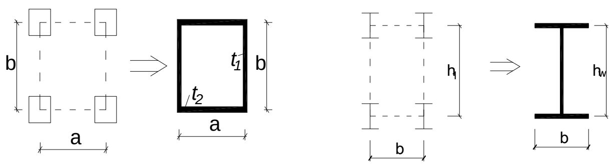


Fig. 4 Equivalent model of column and beam

This method is used on the mega - sub controlled structural system to establish an accurate model and the truss model system, then using the equivalent stiffness principle, mega beams and columns are establish as bar element between each floor. Using the FEMA software SAP2000 a two dimensional equivalent simplified model is establish as shown in fig.2 and fig.3 for MSCSS and MSS respectively, where bar element (beam element) and material properties were selected based on the characteristics of the software [9][10]. SAP2000 can constitute various objects of the structure (point objects, line objects, surface objects, and entity objects).

IV. Numerical Simulation Results

To investigate the effectiveness of the control system for different structures systems, two natural earthquake waves (El Centro (1940) and Taft ground acceleration records) and one artificial ground acceleration record synthesized according to the site measurement and standard response spectrum are used in the numerical simulations. The artificial earthquake ground motion data [11] used in this study is based on Hilbert-Huang Transform (HHT) method. These inputs seismic waves energy are mainly concentrated within the firsts 30s, below 10Hz and the energy and frequency changes details over the time is very clear. The first 6 order periods of the MSS and MCSS structures are presented in table I. The peak ground accelerations (PGA) are scaled to 0.4g, 0.8g, 1.0g and 1.2g. The results of the simulation, calculated by the Nonlinear Direct Integration History method (HHT method) are presented in table II for El Centro waves. The acceleration and displacement response of the mega-sub controlled structure system (MSCSS) with viscous dampers are compared with the corresponding uncontrolled one in Fig.5, 6 and Fig.7, respectively under the El Centro 1940, the artificial and the Taft ground acceleration waves at the top floor of mega-frame structure.

TABLE I
STRUCTURAL PERIOD (S)

Period /s	T_1	T_2	T_3	T_4	T_5	T_6
MSS	2.80625	0.94517	0.54352	0.24062	0.17957	0.13799
MSCSS	1.97027	0.79920	0.65700	0.50398	0.32272	0.20296

From tables, it can be seen that even the MSCSS without dampers can accurately react to strong earthquake motions more than the mega-sub structure (MSS). Table II, Fig.5, 6 and fig.7 depicted the acceleration and displacement response reduction ratio. When subjected to 0.4g, with 4 viscous dampers the acceleration and displacement can be reduce about 22.2% and 21.5% respectively under the El-Centro excitation; and 24.6% and 46.8% when subjected to artificial wave, at the top floor of the mega-frame. To demonstrate the effectiveness of the control system, the same comparisons are made for 0.8g, 1.0g and 1.2g, and almost the same behavior can be observed as for 0.4g. The control ratios are shown in table II (in brackets).
The data illustrate that the structure responses under the excitation of several ground motions are close. It can be seen that the responses of the artificial motion is less than that of El Centro and Taft waves. On others hand, we can remark that the seismic responses of these structures are almost dominated by Taft wave at the top floor of the mega frame while maximum responses are obtained within the rest of the structure under

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:5, No:12, 2011

TABLE II. Maximum acceleration and displacement response values for El-Centro wave

	Mega-frame top floor		2nd sub-structure top floor		1st sub-structure top floor	
MSS						
	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)
0.4g	7.63	0.81	7.16	0.8	4.92	0.63
0.8g	15.21	1.62	14.27	1.61	9.92	1.26
1.0g	16.41	1.89	15.16	1.87	12.06	1.47
1.2gl	20.82	2.09	19.02	2.08	13.78	1.68
MSCSS without dampers						
	Mega-frame top floor		2nd sub-structure top floor		1st sub-structure top floor	
	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)
0.4g	6.68	0.26	6.27	0.23	4.81	0.19
0.8g	13.36	0.52	12.55	0.46	9.62	0.38
1.0g	16.7	0.65	15.69	0.57	12.17	0.47
1.2gl	20.04	0.77	18.83	0.68	14.31	0.57
MSCSS						
	Mega-frame top floor		2nd sub-structure top floor		1st sub-structure top floor	
	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)	Accel(m/s2)	Displ(m)
0.4g	5.19(22.2%)	0.20(21.5%)	4.73(24.6%)	0.20(13%)	3.38(29.7%)	0.12(35.6%)
0.8g	9.77(26.8%)	0.41(20%)	9.33(25.7%)	0.40(12.4%)	7.79(19%)	0.23(40.6%)
1.0g	11.95(28.4%)	0.51(20.5%)	11.61(26.1%)	0.49(13.6%)	9.85(19.1%)	0.27(42.6%)
1.2gl	14.38(28.2%)	0.61(20.4%)	13.74(27%)	0.59(14.3%)	12.05(15.8%)	0.32(42.2%)

Accel: Acceleration; Displ: Displacement

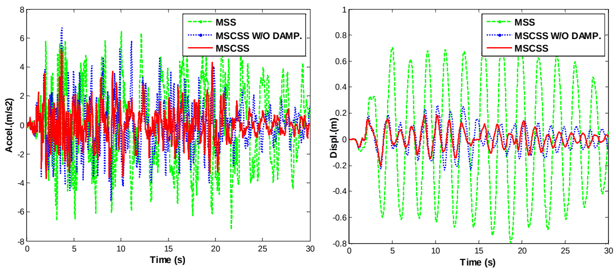


Fig. 5 mega-frame top floor acceleration and displacement under El Centro wave (0.4g)

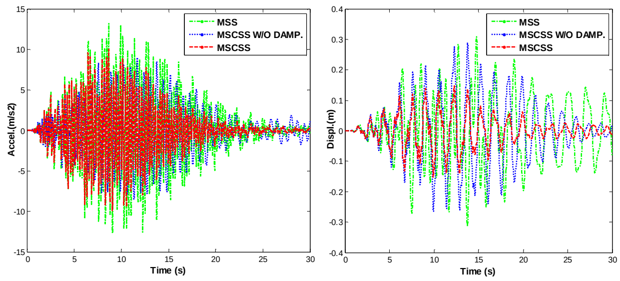


Fig. 6 mega-frame top floor acceleration and displacement under artificial wave (0.4g)

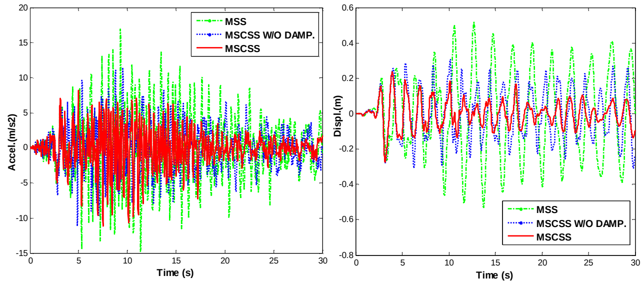


Fig. 7 mega-frame top floor acceleration and displacement under Taft wave (0.4g)

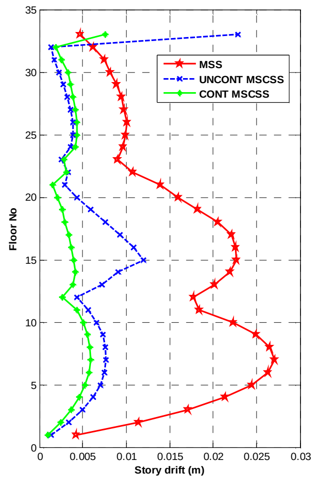


Fig. 8 Distribution of maximum story drift (EI wave)

El-Centro wave.We should however remark that the displacement control effectiveness is more obvious when subjected to the artificial motion than the El-Centro wave. The opposite is observed for the acceleration control. To avoid collision between the main structure and sub-structure of the MSCSS; and also improve the control effectiveness, additional dampers devices can be inserted between the mega-columns and sub-structures (preferably at the middle). However notice that the MSCSS sub-structures has good control results and can satisfy dynamic response criteria.

Further, the X-directional storey drifts of the structures are also investigated during the nonlinear elasto-plastic analysis using the El-Centro ground acceleration wave. The absolute values of maximum story drifts are illustrated in fig.8. The investigation results illustrates that the responses of these structures are close, and almost reasonable. We can see that same as the accelerations and displacements response, the maximum inter-storey drifts values of the MSS is also greater than those of the MSCSS models. The fig.8 shows that MSCSS models have an important story drift at the top of the structures. Also, we can see that except the MSCSS with dampers, the traditional mega-sub structure and the uncontrolled MSCSS models all exceed the allowable values of international code of building security. The maximum story drifts values are approximately evaluated at 1/131, 1/43, 1/37, respectively for the control MSCSS, uncontrolled MSCSS and the MSS model. Nevertheless, this shows once more the controlling capacity and performances of the MSCSS structure systems when subjected to rare earthquake motions.

V. Plastic Hinge and Failure Mechanism

SAP2000 implements the plastic hinge properties described in FEMA-356 and ATC-40. Five points labeled A, B, C, D, and E define the force–deformation behavior of a plastic hinge. The values assigned to each of these points vary depending on the type of element, material properties, longitudinal and transverse steel content, and the axial load level on the element. SAP2000 provides default-hinge properties and recommends PMM hinges for columns and M3 hinges for beams (FEMA-356 and ATC-40). Figure 9 shows the force–deformation relationship of a typical plastic hinge.

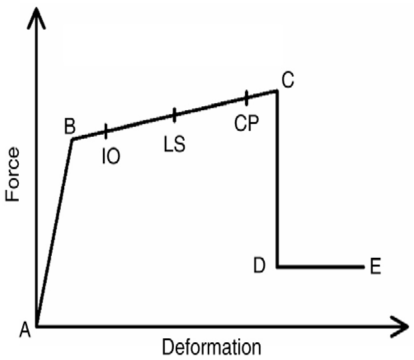


Fig. 9 Force-deformation relationship of typical Plastic hinges

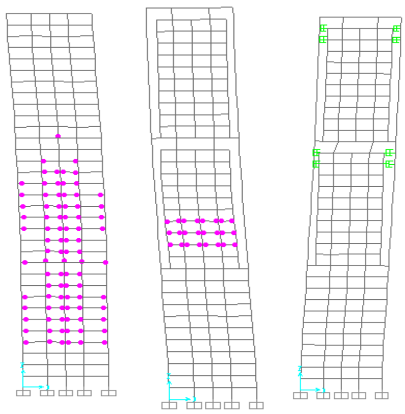


Fig. 10 Plastic hinge distribution: (a) MSS; (b) MSCSS without dampers and (c) MSCSS (EI – 1.0g)

Following the ultimate rotation capacity of a structural element, acceptance criteria are defined; labeled IO, LS, and CP stand for Immediate Occupancy, Life Safety, and Collapse Prevention, respectively (FEMA-356 and ATC-40).

To provide more information about the failure mechanisms in the MSS and MSCSS structures systems, plastic hinge patterns are investigated using these default-hinge properties and compared at different location of structures and at different time step.

For the mega-sub structure (MSS) configuration system, plastic hinge formation starts with beam ends at the 6th and 7th floor, after 20.7s of computation (0.8g), and then propagates to whole structure. The structure will attend the collapse state when subjected to 1.2g of El Centro ground acceleration; when the maximal displacement reaches 2.09m.

When subjected to Taft wave, it is show that plastic hinge formation starts at the 2nd sub-structure for 1.2g after 10s and reaches the 1st sub-structure 10s later but did not collapse.

For the artificial ground motion excitation, plastic hinge formation starts after 13.7s for 1.2g also at the beams ends of the 2nd and 3rd floor of the second sub-structure (top part); but will not reach the collapse state.

The uncontrolled MSCSS configuration system also will starts plastic hinge formation in first sub-structure, 3rd floor beam two ends after 5.9s of 1.0g (El-Centro wave). During the computation, plastic hinge reaches the first sub-structure and the right end of the second mega-beam. The computation stops after 30s for 1.2g.

The analysis of MSCSS with viscous dampers shows that there are significant differences in hinging patterns. The structure did not collapse. This also can demonstrate the effectiveness of the control system on structure under rare earthquake motions. On the other hand, it can be seen that the controlled MSCSS structure can strongly resist to external loads. MSCSS models (controlled model and the uncontrolled one) do not present plastic hinges formation under artificial ground excitation.

The plastic hinging patterns of the MSS and the two MSCSS configuration systems are shown in fig.10. Comparison of these results shows that the yielding state of these structures is similar; hinges locations, damage and failure occurs only at the beams.

Also we can see that at the same time of computation, the number of plastic hinges on the MSS model is much more than the two other structures. Due to the configuration and the functionality of the MSCSS configuration, the mega-frame is expected to have more damage level than the sub-structures. This behavior can be seen in this study. It’s also seen in this study that the damage state almost occurs at beams ends of the MSCSS configuration. To illustrate the control mechanism of the MSCSS, displacement and acceleration responses are also compared at the top floor of the MSCSS and MSS when these structures reached the elasto-plastic state; and depicted in fig.11. The figure clearly shows that MSCSS still have good controlling effectiveness during the elasto-plastic state.

As expected, it shows that the elasto-plastic time-history analysis method can judge the yielding mechanism, weak positions and damaged forms exactly for these structures under strong earthquake action. Although dynamic elasto-plastic analysis accurately indicates the behavior of structure, it is seen that the seismic response of building depends on the input ground motions. If we consider the analysis results as the criterion of judging the security, we can remark that the new MSCSS configuration can accurately meet the requirement, when subjected to rare earthquake excitations.

Analyzing the dynamics responses and comparing with the performance objective, it can be conclude that the mega-sub controlled structure systems can satisfy the performance objective. It is important to notice that not only the controlled MSCSS do not collapse under rare earthquake action, but also presents good seismic resistance ability. This control system can absorb structure dynamic energy, thus reduce structure element section. Therefore it also demonstrates that the mega-sub controlled structure system presents economic advantages.

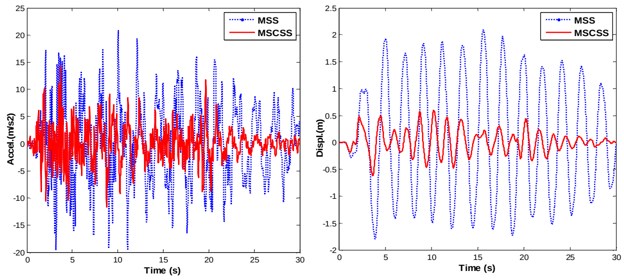


Fig. 11 top floor acceleration and displacement comparison figure at 1.2g (EI wave)

VI. Conclusion

This study is carried out to grasp the seismic performance of the mega-sub controlled structure system (MSCSS) by the nonlinear elasto-plastic time history analysis method when subjected to severe earthquake excitation. The above analysis results clearly show that the MSCSS configuration system presents good control effectiveness.

From this study the following conclusions can be obtained:

1- The structure damage based on SAP2000 software platform can accurately simulate the elasto-plastic performance of the structure, reflect the damaged status and evaluate the integral seismic resistant performance.

2-The MSCSS model can accurately resist to extreme earthquake excitations and also meet international buildings security codes.

3-Viscous dampers not only accurately reduce accelerations and displacement on the structure but also can absorb structure internal forces, thus reduce structure element section.

Acknowledgment

The authors would like to acknowledge the financial contributions received from the National Natural Science Foundation of China (51078311); Doctoral Fund of Ministry of Education of China (20096102110018) and from the Northwestern Polytechnical University through the research fund project (JC200814).

References

[1] M. Q. Feng and A. Mita 1995. Vibration control of tall buildings using mega-sub configuration. ASCE. Journal of engineering mechanics, 121(10): 1082~1087.

[2] W. Chai and Maria Q. Feng. 1997. Vibration control of super tall buildings subjected to wind loads. Int. J. Non- linear Mechanics, 32(4): 657~668..

[3] Zhang. X.A., Zhang. J.L. and Jiang, J.S. 2004. The influence of sub-structural stiffness on the dynamic property of the MSC frame. 2004. Journal of Northwestern Polytechnical University.Vol.22 (1), 2004:59–63

[4] Zhang Xun'an, Wang Dong and Jiang Jiesheng. 2005. The controlling mechanism and the controlling effectiveness of passive mega-sub-controlled frame subjected to random wind loads. Journal of Sound and Vibration, 283: 543-560

[5] Zhang X. A, Qin X. J , Cherry S, Lian Y. D. 2009. A new proposed passive mega-sub controlled structure and response control. Journal of earthquake engineering. 13(2):252—274.

[6] Lian Y. d, Zhang X. A. 2006. The study of dampers in the MSC frame. Industrial Building. Vol. 36(2), 2006:16–19..

[7] Lian Y.D, Zhang X.A, Cherry S 2007. Damping characteristics of friction damped braced frame and its effectiveness in the mega-sub controlled structure system. Earthquake Engineering and Engineering Vibration, 6 (2):171-181.

[8] X. Y. Gao, R. Q. He. 2004. Research on Equivalent Model of Mega-structure. Journal of University of Science and Technology of Suzhou, vol. 16, no. 2, pp, 66—72..

[9] SAP2000 Integrated Finite Element Analysis and Design of Structures, steel design manual, Computers and Structures, Inc. Berkeley, California, USA.

[10] SAP2000 Linear and Nonlinear Static and Dynamic Analysis and Design of Three-Dimensional Structures, Computers and Structures, Inc. Berkeley, California, USA.

[11] Zou Lin 2011. A Study on Reliability for Resisting Seismic Loading Based Structural Optimization of MSCSS. M.S thesis, Northwester polytechnical university..

[12] X. J. Qin, X. A. Zhang and C Sheldon. 2008. Study on semi-active control of mega-sub controlled structure by MR damper subjected to random wind loads. Earthquake Engineering and Engineering Vibration

[13] Xiangjun Qin, Xun'an Zhang. 2009. Vibration controlling characteristics of a New Improved Mega-Sub Controlled Structure subjected to random wind load. In Proceedings of the International MultiConference of Engineers and Computer Scientists 2009 Vol II IMECS 2009, March 18 - 20, 2009, Hong Kong..

[14] FEMA356, The Federal Emergency Management Agency, USA.

[15] GB 5011—2001 (2001). National Standard of the People's Republic of China. Code for Seismic Design of Buildings..