SHAKING TABLE TEST AND ANALYSIS OF CORE-TUBE PARTIAL SUSPENSION STRUCTURE

CAO Wanlin[1] , WANG Min[1] , LU Zhicheng[2] , ZHANG Jianwei[1]

[1] *College of Architecture and Civil Engineering ,Beijing University of Technology，Beijing，China*

[2]*Beijing Electrical Power Construction Research Institute of SGCC，Beijing，China*

Email: wlcao@bjut.edu.cn

ABSTRACT:

The core-tube partial suspension structure is proposed in the paper. It takes advantage of the virtues of both the core-tube suspension structure that is of good earthquake resistant performance and the frame core-tube structure that has more lines of seismic resistance, which is the structure of core-tube suspension with dampers and pure concrete blocks between core tube and suspension floors in upper storeys of sharp seismic responses and frame core-tube in bottom storeys of less seismic responses. The system can achieve effective control to earthquake responses. A shaking table test of a 1/10 reduced scale model of this structure is described in the article. The test procedures went through elastic, elasto-plastic stages of structure. The dynamical model is set up and dynamical characteristics and earthquake responses of the structure under the El Centro wave are analyzed. The experimental results show the structure has good seismic behaviors. Then, the elastic and elasto-plastic time-history analyses of the structure are carried out by SAP2000 and the simulation results fit well with that of experiment.

KEY WORDS: core tube; partial suspension structure; vibration control; shaking table test

1 INTRODUCTION

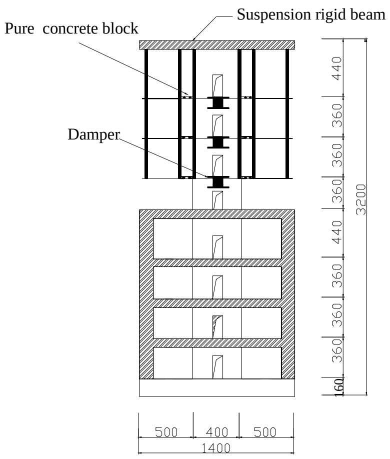
Domestic and foreign experts and scholars in the fields of structural engineering pay much attention to the research on core-tube suspension structure. A number of experimental and theoretical researches have been done (YANG *et al.* 1997, ZHANG *et al.* 1997, ZHANG *et al.* 1997, ZHANG *et al.* 2000, ZHANG *et al.* 2001, ZHOU *et al.* 2005and CAO *et al.* 2006), which indicates that the structure has good seismic reduction properties. At the same time some scholars believe that "this type of structural has weaknesses the main of which is less seismic defense line so it should be treated seriously"(ZHAO *et al.* 2006) Frame-core tube structure currently used in more projects has many seismic defense lines and good seismic performance. So, the core tube partial suspension structure is proposed in the paper. It takes advantage of the virtues of both the core tube suspension structure that is of good earthquake resistant performance and the frame-core tube structure that has more seismic defense lines, which is the structure of core tube suspension structure in upper storeys of sharp seismic responses and frame-core tube in bottom storeys of less seismic responses.

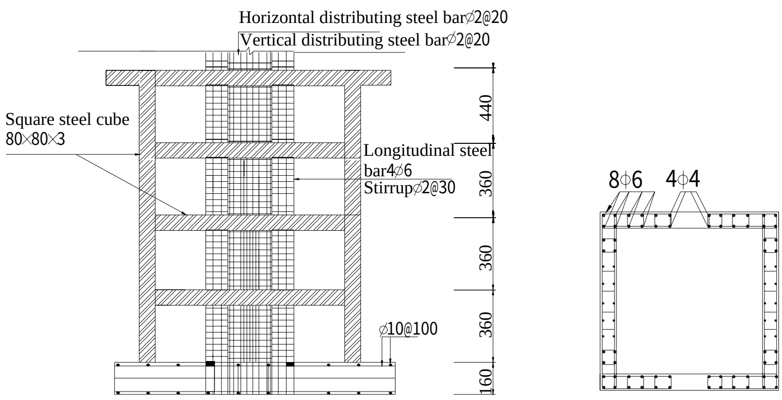
The proposed core tube partial suspension structure is designed as the structure of core tube suspension structure in upper storeys and frame-core tube in bottom storeys. The self-developed "combined dampers with concealed X-type mild steel plate and lead "(CAO *et al*. 2006 and LU *et al*. 2005) and pure concrete blocks are set up between core tube and suspension floors. The design program of structure are: first，realizing control of no destroying under small earthquakes, that is, under small earthquakes, pure concrete blocks does not destroy to maintain the rigid connections between core tube and suspension floors; second，realizing repairable control under middle earthquakes, that is, under middle earthquakes, pure concrete blocks destruct firstly, then damper start-up, remnant concrete blocks and damper participate energy dissipating together, and concrete blocks can be renovated after earthquakes; third，realizing control of no collapse under serious earthquakes, that is, under serious earthquakes, pure concrete blocks destruct completely, then damper start work until damaged seriously, at this time, almost the upper structure become a entire suspended structure to reduce the earthquake response and ensure that the main structure does not collapse.

2 DESIGN OF THE MODEL

One 1/10 scale 8 stories model of core tube partial suspension structure were tested on shaking table. The design of the model are shown in Figure 1.The core tube was designed complying with the current design code, and the reinforcement of lower and upper core tube were same. The design and reinforcement of steel frame are shown in Figure 2.

The model were poured with concrete of strength grade designed as C20 which had a measured cube concrete compressive strength of 26.20 MPa and elastic modulus of 2.55×10^4MPa. The shear strength of pure concrete was 1.2 MPa, elastic modulus was2.4×10^4 MPa. The beams and columns of the bottom frame made use of 80mm×80mm×3mm square steel pipes. Steel blocks were fixed on the structure model in order to conform to the similitude requirements of mass and living loads. The total weight of the model was 72.8kN. The similitude requirements are tabulated in Table 1.





(a) Steel frame (b) Core-tube

Figure 1 Structural model Figure 2 Design of steel frame and reinforcement details of core-tube

Table 1 Similarity coefficients of the model

Physical quantity	Similitude coefficient(model/prototype)
Geometry	1/10
Elastic modulus	1
Stress	1
Mass density	10
Stiffness	1/10
Time	$(1/10)^{1/2}$
Acceleration	1

3 TEST AND ANALYSIS

3.1 Measured Contents

The measured contents of the research included: the dynamic characteristics (frequencies, vibration modes, damping ratios), absolute acceleration of ground and every floors, displacement of the top suspension beam (the eighth floor of the structure) and the middle structure (the fourth floor, the followings are same) compared to the ground, strain of vertical reinforcement on the corner of core tube, strain of the end of steel frame columns at bottom every floors. The model was subjected to the shaking table motions simulating El Centro(1940)N-S earthquake ground motions.

3.2 Experiment Results and Analysis

3.2.1 Frequencies and Damping Ratios

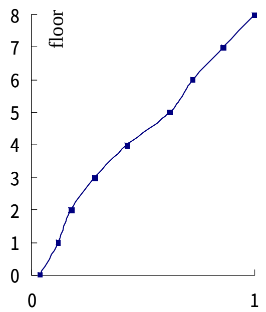
The first frequencies and damping ratios measured at different experiment stages are tabulated in Table 2, where shows that natural frequencies tended to decrease while damping ratios tended to increase along with the ground motions more and more violent. Under the 8 degree seldom occurred earthquake, the core tube cracks continually developed and the plastic deformations gradually increased, which resulted in significant decrease of first frequency. After earthquake wave of the largest peak acceleration entered, in addition to cracks throughout the root of core tube and a crack at welding place on bottom steel frame column, other parts had no significant damage, the overall structure had not more serious damage so the frequency continuous decline degree of overall structure was not obvious.

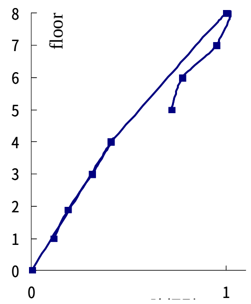
Table 2　Frequencies and damping ratios of the structural model

Test phase of dynamic characteristic	First frequency f_1/Hz	First damping ratio ξ_1/%
1. Before earthquake excitation (having pure concrete blocks and dampers)	6.711	1.302
2. Before earthquake excitation (only having pure concrete blocks, not dampers)	6.700	1.089
3. 8 degree basic intensity earthquake(pure concrete blocks are disabled)	5.882	1.761
4. After 8 degree seldom occurred earthquake excitation, cracks appeared at the root of core tube	4.950	1.823
5. After final damage	4.587	2.071

3.2.2 Vibration Mode

Figure 3 shows the first vibration mode of the model before test (having pure concrete and damper). Figure 4 shows the first vibration mode of the model when the main structure was in an elastic stage after 8 degree basic intensity earthquake motion. Figure 5 shows the first vibration mode of the model when the root of core tube appeared cracks after 8 degree seldom occurred earthquake motion. Figure 3 shows that, at the initial stage the first vibration mode of the suspension structure and the general structure were similar because the linking stiffness of pure concrete blocks between core tube and upside suspension floor was great. Figure 4 shows that, under the 8 degree basic intensity earthquake, the main structure was in an elastic stage. Because the pure concrete blocks between core tube and upside suspension floor had been damaged, the linking stiffness had degraded. But the first vibration mode of the main core tube still approached a straight line. Figure 5 shows that, under the 8 degree seldom occurred earthquake, the damper fully played damping and energy-consuming role. Although the vibration mode of the main structure was nearly a straight line, the upside suspension floors had greater response.





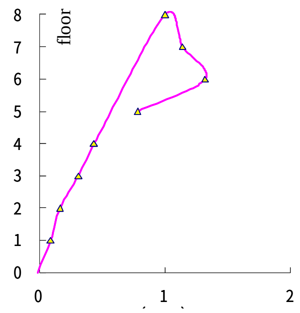
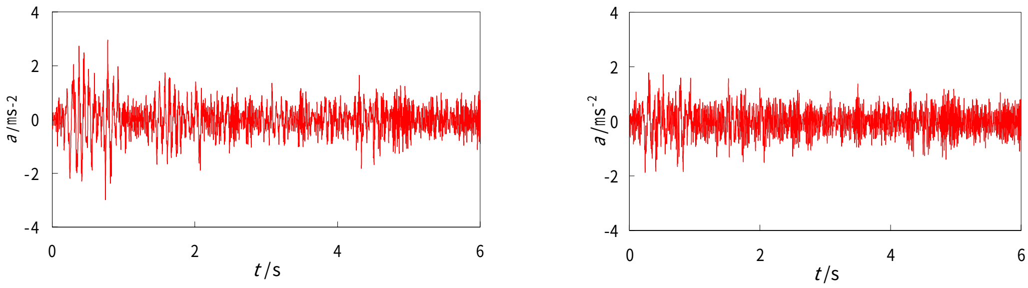


Figure3 The first shape before experiment Figure 4 The first shape in elastic phase Figure5 The first shape after cracking on root of core-tube

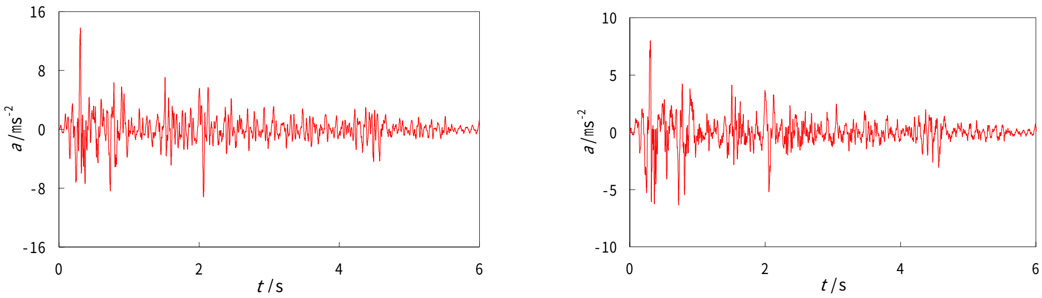
3.2.3Acceleration Response

Acceleration response time-history earthquake curves of the top and the middle structure under 8 degree frequently occurred earthquake and 8 degree seldom occurred earthquake are shown in Figure 6 and Figure 7 respectively. It is appeared that under 8 degree frequently occurred earthquake, the peak acceleration of the top and the middle fourth floor was 1.96 and 1.24 times bigger than that of the table respectively. Under 8 degree seldom occurred earthquake, the peak acceleration of the top and the middle fourth floor was 1.67 and 1.03 times bigger than that of the table respectively. Cracks mainly appeared at the intersection of core tube and table floor. Upper core tube was no obvious cracks and damage. The elastic-plastic deformation energy-consuming effect of the main structure was small. So the plastic deformation of the dampers played an important role in the damping and energy-consuming.



(a)Time-history curve of the top (b)Time-history curve of the middle fourth floor

Figure 6 Absolute acceleration responses under intensity 8 frequently occurred earthquake



(a)Time-history curve of the top (b)Time-history curve of the middle fourth floor

Figure7 Absolute acceleration responses under intensity 8 seldom occurred earthquake

3.2.4 Displacement Response

Under 8 degree frequently occurred intensity earthquake, 8 degree basic intensity earthquake and 8 degree seldom occurred intensity earthquake, maximum displacement of the top relative to base （*DWY*）and maximum displacement of the middle fourth floor relative to base（ZWY）are shown in Table 3. It can be seen from Table 3 that under 8 degree frequently occurred intensity earthquake, the top and the middle fourth floor drift of core tube was 1/3404 and 1/3040 respectively; under 8 degree basic intensity earthquake, the top and the middle fourth floor drift of core tube was 1/1206 and 1/1160 respectively; under 8 degree seldom occurred intensity earthquake, the top and the middle fourth floor drift of core tube was 1/749 and 1/685 respectively. The displacements met corresponding request of the current design code *GB50011-2001*, which showed that the structure had good damping effect.

Table 3 Maximum displacements of the structural model

Test state	*DWY*/ mm	*ZWY*/mm
Before 8 degree frequently occurred earthquake excitation	0.893	0.500
Before 8 degree basic intensity earthquake excitation	2.520	1.310
8 degree seldom occurred earthquake	4.059	2.219

4 CALCULATED ANALYSIS

The shaking table test of the structure could be divided approximately into elastic stage and elasto-plastic stage, according to which elastic and elasto-plastic time-history analysis could be done respectively.

4.1 Elastic Time-history Analysis

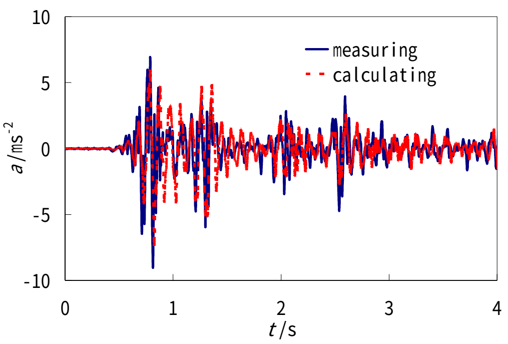
Time-history analysis of elastic stage had been done by structural analysis procedure *SAP2000*. In the structural analysis model, it was assumed that the flexural stiffness of suspension beams and the in-plane stiffness of the floors were infinite. Walls of core tube was simulated using 4 nodes rectangular element; suspension beam was simulated using beam element; steeve was simulated using rod element; pure concrete blocks was simulated using 4 nodes rectangular element; frame beam and column were simulated using beam and column element respectively. The elastic modulus of reinforced concrete was determined according to elastic modulus of composite materials. The formula is $E = \rho_c E_c + \rho_s E_s$

Where ρ_c、E_c are volume ratio and elastic modulus of concrete respectively; ρ_s、E_s are volume ratio and elastic modulus of reinforced concrete respectively. The calculated first frequency of the model before test (having pure concrete and damper) and comparison with measured value are listed in Table 4 as I. After 8 degree basic intensity earthquake motion the main structure was in an elastic stage. The calculated first frequency of the model and comparison with measured value are listed in Table 4 as II.

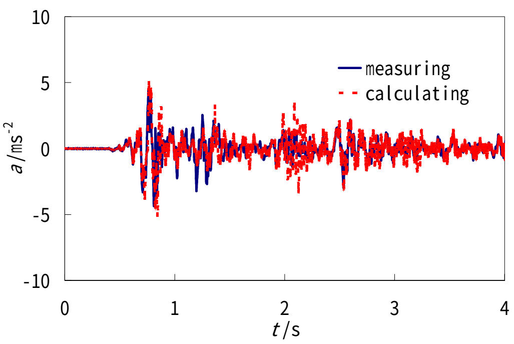
Table 4 The first Frequencies of test and calculation results

Test phases	Measured the first frequency	Calculated the first frequency	Relative error/%
I —— Before test(having pure concrete blocks and dampers)	6.711	7.042	4.9
II —— The main structure is in elastic phase	5.882	6.211	5.6
III —— Cracks appeared at core tube	4.950	4.902	-1.0
IV —— After final damage	4.587	4.673	1.9

When the main structure was in an elastic stage, the comparison of time-history curves of the top and the middle fourth floor are shown in Figure 8. It can be seen from Figure 8 that in an elastic stage the calculated acceleration response results were in good agreement with the measured results.



(a)Time-history curve of the top



(b)Time-history curve of the middle fourth floor

Figure 8 Elastic absolute acceleration responses of test and calculation results under El Centro wave

4.2 Elastro-plastic Time-history Analysis

Time-history analysis of elastro-plastic stage had been done by structural analysis procedure *SAP2000*. The calculated first frequency of the model at cracking stage and comparison with measured value are listed in Table 4 as III. The calculated first frequency of the model after the final destruction and comparison with measured value are listed in Table 4 as IV. It can be seen that the calculated results and the measured results were in good agreement.

After the pure concrete blocks connected the core tube and suspension floors were damaged, damper could fully play the role of energy-consuming, and the final damage of core tube occurred only in the root. In the calculation, nonlinear shear wall element used macroscopic finite element model. Multi-vertical-truss-element model was been used in plastic hinge region at the root of wall (VULCANO *et al.* 1988 and WANG *et al.* 2002), which is shown in Figure 9. The designed pure concrete block mainly was used to bear shear force, so the pure concrete block used shear spring model to simulate (CHEN *et al.* 2005). The self-developed "combined dampers with concealed X-type mild steel plate and lead" used link element to simulate. The calculated acceleration response results in elastro-plastic time-history analysis were in good agreement with the measured results, which is shown in Figure 10.

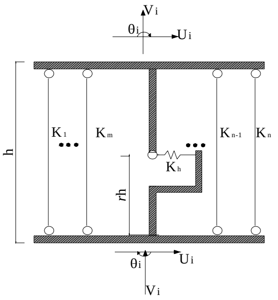
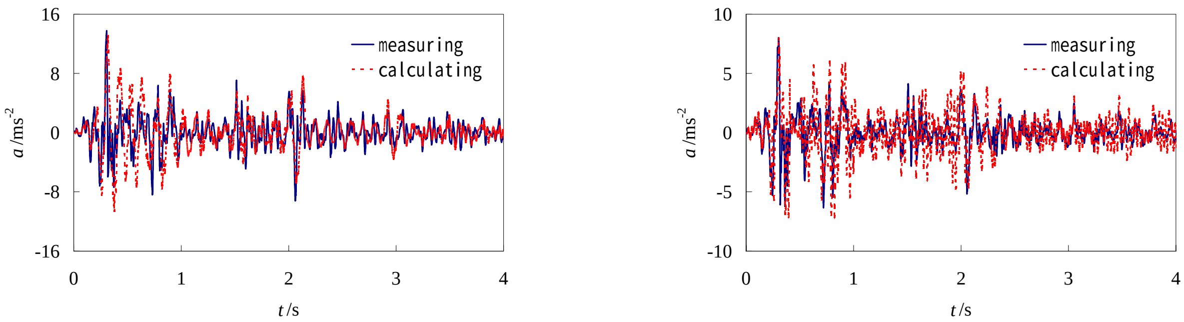


Figure 9 Multi-vertical-truss-element model



(a)Time-history curve of the top (b)Time-history curve of the middle fourth floor

Figure 10 Elasto-plastic acceleration responses of test and calculation results under El Centro wave

5 CONCLUSIONS

(1) The proposed core-tube partial suspension structure has good damping property.

(2) The designed "combined dampers with concealed X-type mild steel plate and lead" has good damping and energy-consuming property.

(3) The model for theoretical calculation is reasonable, the calculated results and the measured results are in good agreement.

(4) It can be seen from the final damage form of the structure that the final damage of main structure occurred only in the intersection of the root of the core tube and bottom floor, where cracks were formed throughout the root. So there became a weak part of the structure, and it should be strengthened. The design method of shear wall and core tube with concealed bracing proposed by author can significantly increase the seismic

performance of shear wall and core tube (CAO *et al.* 2002, 2005 and ZHANG *et al.* 2004). Experiments show that concealed bracing can improve the structure ability to resist shear, bending and slip of basement. The more important is that it can expand the plastic hinge region of structure to enhance its seismic energy-consuming capacity, so this seismic design method can be used as reference.

ACKNOWLEDGEMENTS

This paper was supported by Creative Talent Foundation of Beijing Municipal College（05004311200501）and Academic Innovation Team Foundation of Beijing Municipal College（05004012200515）

REFERENCES

YANG Yun-biao, SONG Qi-gen. (1997) .Two problems on hanging structure with single core tube. *Industrial Construction* **27:12**,10-13

ZHANG Hui, ZHU Bo-long, SU Shao-jun. (1997) .Research on vibration absorption control system of suspension structure. *Journal of Building Structures* **18:5**,59-65

ZHANG Yao-hua, LIANG Qi-zhi, FU Gan-qing. (2000) .The earthquake resistant philosophy and initial design of mega-frame with suspension systems. *Engineering Mechanics* **17:2**,10-17

ZHANG Jin, LÜ Zhi-tao. (2001) .Earthquake simulation test of short-leg shear wall tube mode. *Journal of Southeast University* **31:6**,4-8

ZHOU Jian, WU Xiao-bo.(2005). A study of model-frequency behavior of core-wall suspension structure.*Engineering Mechanics* **22:1**,74-81

CAO Wan-lin, LU Zhi-cheng. (2006) .Experimental investigation on shaking table of core-wall suspension structure with three-term control device. *journal of Beijing university of technology* **32:2**,155-160

ZHAO xi-an. (2000). Modern high-rise building design(the first volume), Science Press, Beijing, China

CAO Wan-lin, LU Zhi-cheng. (2006) .Combined dissipators with concealed X-type steel plate and lead. *Patent Office of the People's Republic of China*, ZL200420118884.2.

LU Zhi-cheng, CAO Wan-lin. (2005) .Experimental study of combined dissipators with concealed X-type mild steel plate and lead. *World Earthquake Engineering*, **21:3**, 45-51

VULANCO A, BERTERO V V, COLOTTI V. (1988) .Analytical modeling of R/C structural walls. *Procs. 9th WCEE* Vol.6.41-46

WANG Meng-fu, ZHOU Xi-yuan. (2002) . The improved parallel muti-component model for the nonlinear seismic response analysis and its application. *Journal of Building Structure* **23:1**,38-42

CHEN Qin，QIAN Jia-ru. (2005) .Static elasto-plastic analysis of RC shear wall with one row opening. *Journal of Computational Mechanics* **22:1**,13-19

CAO Wan-lin, ZHANG Jian-wei, TIAN Bo-fa, et al. (2002) .Experimental study of seismic behavior of mid-rise RC shear wall with concealed bracings. *Journal of Building Structure*s **23:6**,26-32

CAO Wan-lin, HUANG Xuan-ming, LU Zhi-cheng et al. (2005) .Experimental study of seismic behavior of RC core-tube with concealed bracings. *Earthquake Engineering and Engineering Vibration* **25:3**,81-86

ZHANG Jian-wei, CAO Wan-lin, TIAN Bo-fa, et al. (2004) .Earthquake simulation test of RC shear wall with concealed bracings and large space on the ground floor. *Journal of Building Structures* **25:6**,44-51