Experimental Study on the Outrigger Damping System for High-Rise Building

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SUMMARY:
A novel energy-dissipation system for frame-core tube structure equipped with damped outriggers is studied experimentally. A steel frame-core tube structure model is designed and manufactured, in which viscous dampers are inserted vertically between the outrigger and fame columns to make full use of motion discrepancy of these two components. Shaking table tests of the building with damped or fixed outriggers is carried out and compared for a set of earthquake records with various PGAs. 3D finite element models, representing the test models of the structure have been developed in SAP2000. A modified analytical model of dampers is proposed and used in numerical simulation, exhibiting improved agreement with experimental results. The results of shaking table test of the novel energy-dissipation system show the damped outrigger system can achieve a better performance than the fixed outrigger structure in reducing the seismic responses of the structure. Thus, the damped outrigger system provides an economical and effective strategy for improving the performance of the frame-core tube structure under earthquake excitation.

Keywords: damper; outrigger structure; shaking table test; high-rise building.

1. INTRODUCTION

In recent years, taller and more slender buildings are being built across the world. It is becoming critically important to suppress the dynamic response of structures and improve their safety under earthquakes. Passive supplemental damping systems strategies for high rise building, including the viscous dampers, viscoelastic dampers, etc, are well understood and are widely accepted by the engineering community as effective means for mitigating the effects of dynamic loading [Soong and Spencer(2002), Spencer and Nagarajaiah (2003)]. Traditionally, supplemental damping systems are equipped between adjacent floors and are arranged throughout over the height of the structure. For a high-rise building structure, quite a large number of dampers are required for a designed level of performance, which is not economical. On the other hand, as the interstory drift and velocity is relatively low for super high-rise building, performance of damper is restricted.

The outrigger system has been proved to be highly effective to improve the seismic performance of super high-rise buildings by simply engaging the exterior columns to aid in resisting part of the overturning moment resulting from lateral loads [Smith (1981)]. To further improve the dynamic response of structure, a new damping system that adding viscous dampers between outriggers and perimeter column is presented by Smith and Willford [Smith and Willford (2007)]. Jeremlah theoretically investigates the frequency-based response of the damped outrigger system based on a simplified cantilever-beam-with-rigid-outrigger model [Jeremiah (2006)]. Cheng studies performance of the damped outrigger system incorporating MR dampers [Cheng et al (2009)]. So far, the novel outrigger damping system has been successfully applied to two 210 m high buildings in Philippine [Willford et al (2008)].

This paper presents the experimental work on the outrigger damping system, which is carried out at Guangzhou University. A steel frame-core tube structure model is designed and manufactured, in which viscous dampers are specially made and inserted vertically between the outriggers and the perimeter columns to make full use of the motion discrepancy of these two components. Shaking table tests of the building model with damped and fixed outriggers are carried out for a set of earthquake records with various PGAs, so as to experimentally evaluate the performance of the novel damping system. In addition, modeling work is conducted to represent the test models of the structure and viscous damper more reasonably in this study.

2. EXPERIMENTAL SETUP

The test structure used in this study is an eight-story, steel frame-core tube structure model, as shown in Fig. 1. The overall dimensions of the test model are 1600mm by 400mm in plan and 7200mm in height. Thus, the height-to-width ratio of the model is 18, which is corresponding to a flexible high-rise building. Outriggers are located at the 4th floor and 8th floor, respectively. At the both ends of outrigger, small viscous dampers are equipped vertically with the frame columns. There are total of eight fluid viscous dampers employed in this study, which are specially made for the shaking table test by Shanghai Research Institute of Material. The outrigger beam end can be fixed with frame columns by tightening bolts. The size of steel core tube is 200mm by 400mm and the wall thickness of the steel tube is 8mm. Four frame columns have a constant box cross section of 50mm×50mm over the height of the structure. Each floor comprises a 12mm thick steel slab. The whole test model is made up of Q345 steel. Moreover, a concreter block of 280 kg is fixed on each floor as additional artificial mass.

Experimental investigations are performed in the Earthquake Engineering Research and Test Center of Guangzhou University. The 3m by 3m shaking table made by MTS, is of 6 degrees of freedom, whose maximal allowable loading is 25 ton.

Accelerometers are mounted at each floor center to measure the responses of the test model and dampers. In order to obtain the damper strokes, displacement transducers and speed sensors are installed at both ends of the dampers. In this study, The Danish 4381V charge accelerometer and NEXUS 2692-014 charge amplifier are used to measure the acceleration and displacement. Strain gauges are also bonded at the column bases, the bottom of the core tube and the outrigger-ends, which are collected by SPIDER8 acquisition system.

Figure 1. Steel frame-core tube building model on a shaking table

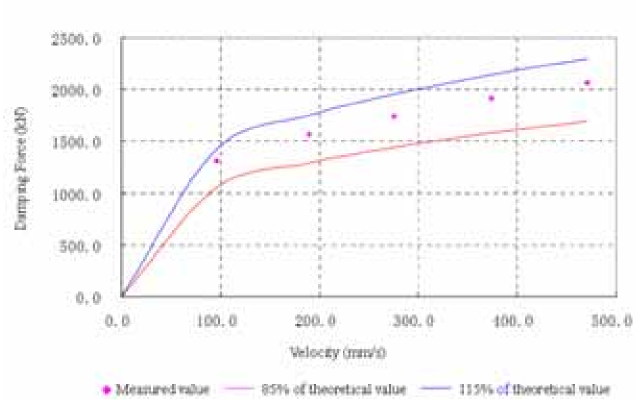


Figure 2. Force-Velocity relationship of viscous damper

3. PERFORMANCE TEST OF VISCOUS DAMPER

Nonlinear viscous dampers are disigned and specailly made for this test, which has a damper force limit at large structural velocities while providing sufficient supplemental damping. Nonliear viscous damper can be easily modeled using a damper element, whose general mechanical form can be expressed as

$$u(t) = c_{\alpha}\left|\dot{d}\right|^{\alpha} \operatorname{sgn}(\dot{d}) \tag{3.1}$$

where $\dot{d}$ is the piston velocity across the damper and c_{α} is the experimentally determined damping coefficient with the units of force per velocity raised to the α power. In Eq. (3.1), α is a constant controlling damper nonlinearity with its range between 0 and 1, and $\text{sgn}(\cdot)$ is a signum function. When $\alpha = 1$, Eq. (3.1) becomes $u(t) = c_1 \dot{d}$, which represents a linear viscous damper. When α is close to zero, the nonlinear viscous damper behaves as a pure friction damper. The design damping coefficient of dampers used in this study is 2500, and the piston velocity power is 0.3 so that the maximum damping forces do not exceed the limit of 2000 N.

A set of high-frequency cyclic test of these fluid viscous dampers are performed in Shanghai Research Institute of Material, before they are used in this study. Fig. 2 shows the force-velocity response of a typical fluid damper employed in this study. It can be observed that the relationship between the measured damping force and the piston velocity exhibits an obvious bilinear trend, and the measured datum are in general agreement with the theoretical results between the velocity region of 100 mm/s to 500 mm/s.

4. DYNAMIC CHARACTERISTICS OF THE TEST MODEL

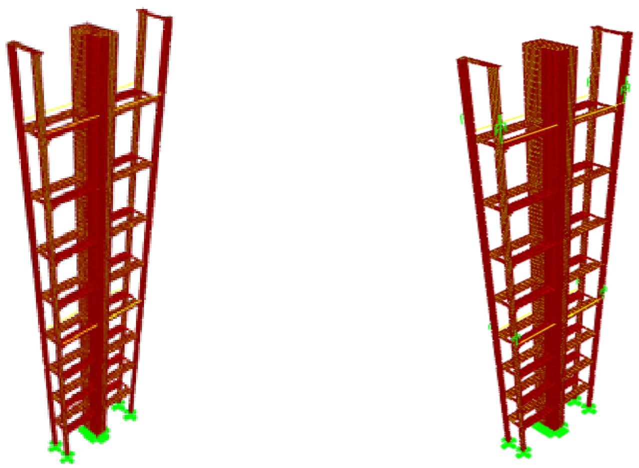
A sine sweep vibration test is conducted to search for the natural periods of the test models. Table 1 shows the measured natural periods and damping ratios of the experimental structure model with fixed and damped outriggers. It can be noticed that in the case of the damped outrigger, both the fundamental period and damping ratio of the model are increased, and the increase in damping ratio is much higher, indicating that the outrigger damping system can offer additional high-damping level to the structure model.

A comparison of the experimental results with those obtained from a finite element analysis is also made in this study. The 3D finite element models representing the test structure models with damped or fixed outrigger respectively have been developed in SAP2000 as shown in Figure 3. Shell elements are chosen to model core, floor and perimeter column, and outrigger beam due to its reasonable accuracy and efficiency. The analytical value of model's fundamental period is also provided in Table 1, which matches well with the experimental result. That means the developed 3D FE model for the test structure is quite reasonable. However, the error for the damped outrigger system is a bit higher, suggesting that the analytical model for nonlinear viscous damper is not accurate enough.

Table 1 Dynamic properties of the test model with fixed and damped outriggers

Model	Fundamental period (s)	Damping ratio
Fixed-Outrigger	0.485(0.474)	0.010
Damped-Outrigger	0.55(0.51)	0.054

*() is analytical value.

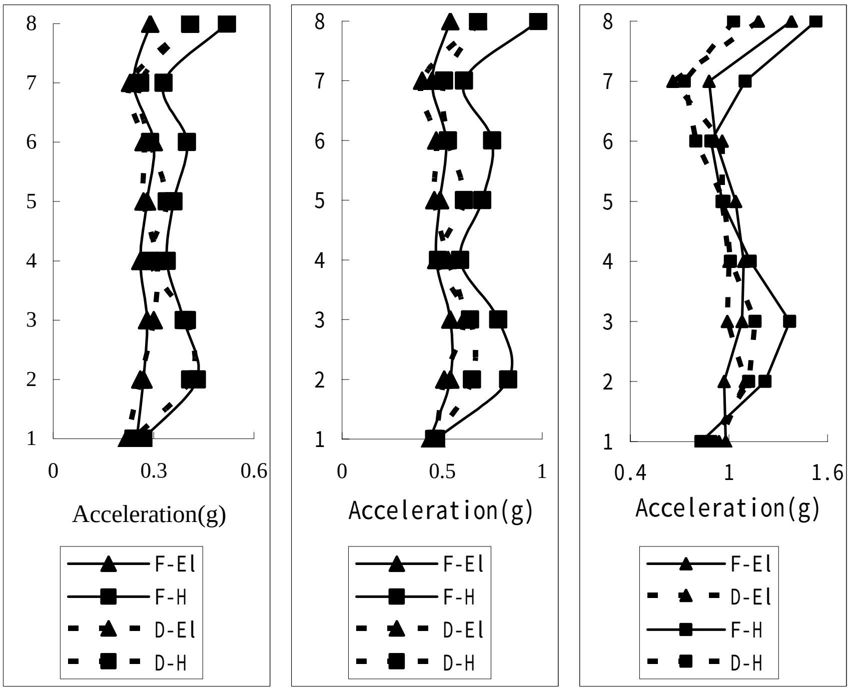


(a) Fixed-Outrigger model (b) Damped-Outrigger model

Figure 3. 3D FE model of frame-core system with fixed and damped outriggers

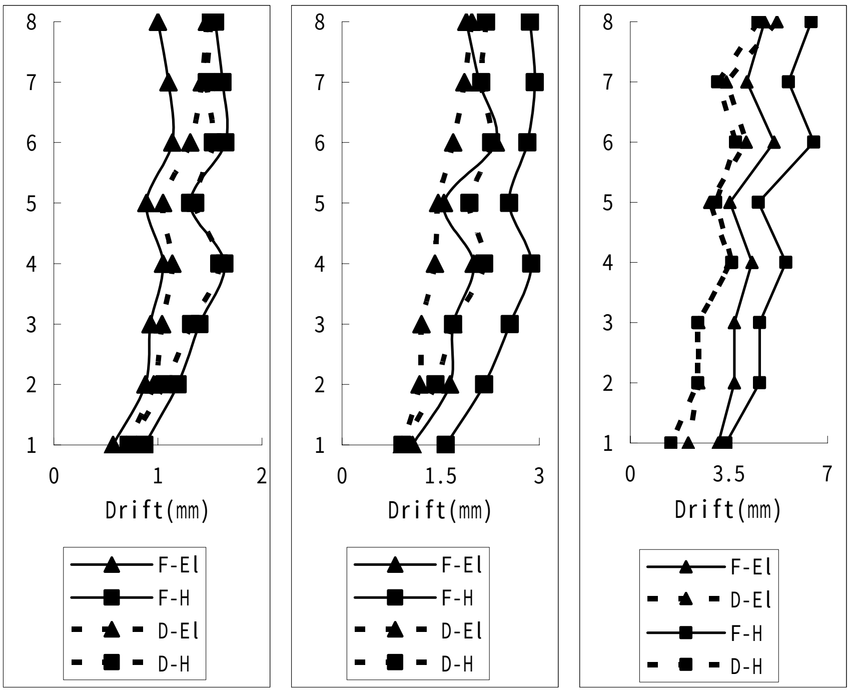
5. EXPERIMENTAL RESULTS

The El Centro (1940, NS) and Hollywood (1971, NS) earthquake records are scaled as the input ground motions of the shaking table tests. The PGA of these motions is increased from 0.2g, 0.4 to 0.6g to investigate the performance of the novel outrigger damping system under small, medium and strong earthquakes. The steel structure model is designed to be strong enough so that the structure remains elastic in the test.



(a) 0.2g (b) 0.4g (c) 0.6g

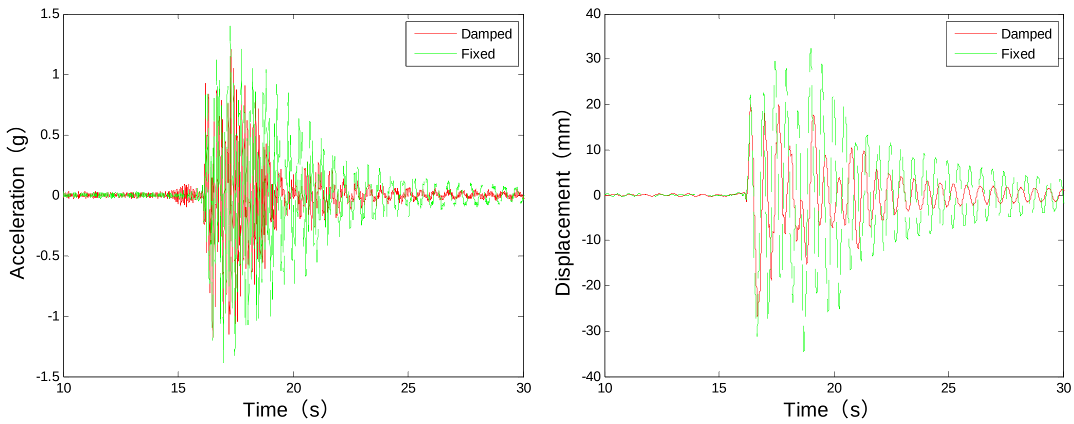
Figure 4. Story acceleration envelope



(a) 0.2g (b) 0.4g (c) 0.6g

Figure 5 Interstory drift envelope

Peak accelerations, interstory drifts obtained for scaled El Centro and Hollywood records are shown in Figure 4-5. Notice that both quantities are reduced significantly for the novel damped outrigger system. Moreover, it can be observed from the experimental results that the better damping effect can be achieved with the increasing PGA of ground motion. This is primarily due to an increased ability to dissipate seismic energy, not to a shift in frequency.



(a) Roof acceleration (b) Roof displacement

Figure 6. Time history responses of test structure with fixed and damped outrigger under El Centro 0.6g motion

Top story acceleration and displacement responses of test structure for the El Centro PGA 0.6g test are provided in Fig. 6. It is clear that both roof acceleration and roof displacement of the damped outrigger system are much lower than those of the fixed case. Especially, displacement is reduced dramatically, which is important for the safety of structure. The seismic energy input to the structure may diminish due to the loosening associated with special connection. In addition, the additional damping system can make full use of dampers and greatly enhance the ability of the structure to dissipate energy. The novel outrigger damping system offers a cost-effective means for high-rise building.

Table 2 Peak strain of structure model under 0.6g ground motions

Record / Location	El Centro			Hollywood		
	Fixed	Damped	Effectiveness	Fixed	Damped	Effectiveness
Column base	276.2	166.3	39.79%	279.6	151.7	45.75%
Tube bottom	361.4	253.9	29.75%	363.1	194.6	46.40%
4^{th} outrigger	474	173.3	63.44%	446.4	167.8	62.42%
8^{th} outrigger	301	161	46.49%	414.7	140.9	66.03%

Table 2 compares strain responses of the structure model with fixed and damper outrigger under 0.6g ground motions. In the case of the damped outrigger, strains of steel columns and core tubes at different floors are reduced in various extents. It also can be observed that strain at outrigger is decreased substantially due to the stress relief for the damped outrigger system. Both bottoms of column and core tube are reduced by around 40%. This phenomenon is due to the beneficial effect of the novel energy system, where a viscous damper works as a connecting component, as well as an energy dissipation unit.

Comparisons are also made between the experimental datum and results from time history analysis that employed the 3D finite element model. Preliminary analysis indicates the analytical model expressed in Eq. (3.1) may result in larger error under low amplitude excitations, although it works well for strong ground motion. When the motion discrepancy between two ends of a damper is small, oil compressibility, inner bubble and piston friction are crucial for the performance of damper, which is not considered by the general analytical model of viscous damper. This paper presents a modified analytical model for viscous damper in low amplitude motion. As shown in Fig. 7, friction element simulates all the internal friction, spring element K_b and K_d modeling the inner bubble and oil compressibility, respectively, and dashpot representing the damping effect.

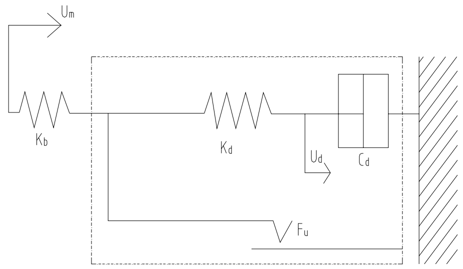


Figure 7. Modified Analytic model of viscous damper

Table 3 Interstory drift of damped outrigger system under Hollywood 0.4g motion

story	Before modified			After modified		
	Analytical	Experimental	Error	Analytical	Experimental	Error
1	0.61	0.92	33.7%	0.73	0.92	20.7%
2	0.93	1.42	34.5%	1.22	1.42	14.1%
3	1.2	1.69	29.0%	1.36	1.69	19.5%
4	1.55	2.16	28.2%	1.68	2.16	22.2%
5	1.68	1.94	13.4%	1.71	1.94	11.9%
6	1.72	2.27	24.2%	1.85	2.27	18.5%
7	1.69	2.12	20.3%	1.82	2.12	14.2%
8	1.64	2.19	25.1%	1.77	2.19	19.2%

Table 3 shows comparisons of the selected experimental responses with the analytical results corresponding to both the general and modified analytical models of viscous damper, respectively. One can see that when the modified analytical damper model is employed, the error between the analytical and experimental results is diminishing significantly, suggesting the importance of using a modified analytical damper model.

6. CONCLUSION

A novel energy-dissipation system for frame-core tube structure equipped with damped outriggers is studied experimentally. A steel frame-core tube structure model is designed and manufactured, in which small viscous dampers are inserted vertically between outriggers and frame columns. Shaking table tests of the building model with damped and fixed outriggers are carried out for a set of earthquake records with various PGAs. Experimental results show that the damped outrigger system can achieve a better performance than the fixed outrigger structure in reducing the seismic responses of the structure, and the advantage over the fixed case is strengthened with the increasing PGA of input ground motion. Further, analytical work shows the developed FE model can represent the test structure model very well. A modified analytical model for viscous damper can simulate the behavior of viscous damper more accurately, where oil compressibility, piston friction, etc, are comprehensively incorporated. The novel outrigger damping system provides an economical and effective strategy for improving the performance of the frame-core tube structure under earthquake excitation.

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