The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Advances on structural vibration control in civil engineering

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ABSTRACT

In recent years, much attention has been paid to research and development of structural control techniques with particular emphasis on alleviation of wind and seismic response of buildings and bridges in China. Structural control in civil engineering has been developed from the concept into a workable technology and applied into practical engineering structures. The aim of this paper is to review a state of the art of researches and application of structural control in civil engineering in China. It includes the passive control, active control, hybrid control and semi-active control. Finally, the possible future directions of structural control in civil engineering in China are presented.

1 INTRODUCTION

The structural control system is commonly classified by its device type resulting in four general control types: passive, active, hybrid and semi-active control. An active control system is one in which an external source power control actuators that apply forces to the structure in a prescribed manner. A passive control system does not require an external power source. The hybrid control implies the combined use of active and passive control systems. Semi-active control systems are a class of active systems in which only small magnitude of external energy is needed to change the parameters of control system.

In recent years, serious efforts have been undertaken in structural control and fruit achievements have been made in China. Structural control has been developed from theoretical analysis and experimental research into engineering application. In this paper, the state-of-art of vibration control techniques, including theoretical and experimental studies, practices in civil engineering are reviewed. The possible future directions of structural control in civil engineering are discussed.

2 PASSIVE CONTROL

2.1 *Base isolation*

The application on seismic isolator in China has proved that the isolation system is more safe, economic and reasonable than the traditional structural system. More than 500 full-scale implementations of base isolated buildings and bridges have been accomplished to alleviate their earthquake and traffic induced response so far (Ou 2004). Design principle of base isolation and energy dissipation are also included in Code for Seismic Design of Buildings published by the agency of Ministry of Construction in 2001. The design codes for base isolated highway bridges and base

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isolated railway bridges were also published by the agencies of Ministry of Transportation and Ministry of Railway.

In order to solve some problems for more wide application of isolation, a great numbers of tests for rubber bearings and shaking table tests for building modes were carried out. In case of a seismic isolated building with a large height-to-width ratio (HWR), the overturning moment at the level of seismic isolated layer could be sufficient enough to exceed the overturning resistance supplied by the gravity, which may result in disconnection of bearings from the superstructure so as to be able to produce an internal damages of rubber layers, even lead to a destroy of the entire building. Li and Wu (2006) investigated the limits of the HWR for isolated building with the laminated rubber bearings under different conditions subjected to earthquake excitations. Most structures are simplified as planar models in base isolation design. However, a lot of structures are eccentric. The earthquake is essentially multi-dimensional and so is the structure response excited by earthquake, which will result in the torsionally coupled vibration that cannot be neglected. Based on many numerical analyses on different soil sites during the action of earthquakes, simplified formulate of torsional seismic actions for base-isolated eccentric structures are presented.

2.2 *Energy dissipation*

Friction provides an excellent mechanism for energy dissipation and has been used for many years in automotive brakes to dissipate kinetic energy of motion. Helix friction dampers have been developed by Huazhong University of Technology. This kind of dampers are made of ordinary materials with simple mechanical structures, hence they are applicable for multi-story and high-rise buildings. Zhang and Yang (1997) presented multi-level friction dampers to satisfy the energy dissipation requirements for earthquake in different intensities. Wu and Ou (1998) presented a kind of pseudo friction damper to reduce effects from additional stiffness in Pall friction dampers.

Zhou (1999) developed innovative bend-shear and shear type lead dampers which can attenuate the vibration of buildings both in mild and strong earthquakes.

Fluids can also be used to dissipate energy, hence many kinds of viscous fluid dampers have been proposed. Commercial viscous fluid dampers with different capacities are also available in China. Recently, 73 sets of viscous fluid dampers manufactured by Taylor Company were installed in Beijing Yintai Center.

Li (2006) presented a new idea of designing mild metallic damper which is called bi-directional mild steel dampers as shown in Fig. 1 and Fig. 2. It is that to strengthen the initial stiffness by extending the steel plate of the damper in its own plane and to increase the energy-dissipating ability by changing the geometric shape of the steel plate of the damper. Results from theoretical analysis and quasi-static experiments showed that these types of mild metallic damper not only provide certain stiffness in normal use, but also are of good ability of the seismic energy dissipation.

2.3 *Tuned mass damper*

The concept of the tuned mass damper (TMD) consists of a secondary mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that increases damping in the primary structure. The frequency of TMD should be tuned to the same as the one of the controlled structures to get the best control results. During an earthquake, TMD will move against the direction of main structural vibration and an inertia force will be acted on the structure to reduce the response of the structure. One TMD can attenuate only the first mode response of a structure with its frequency tuned to the fundamental frequency of the structure. However, the first several modes of a high rise structure are primary and the anticipated response reduction cannot be achieved if only the first mode is controlled. Li et al. (1997) presented the method of using multiple TMDs to control multiple modes of structures and got obvious results. TMD control system was applied in Zhenzhou International Conference and Exhibition Center.

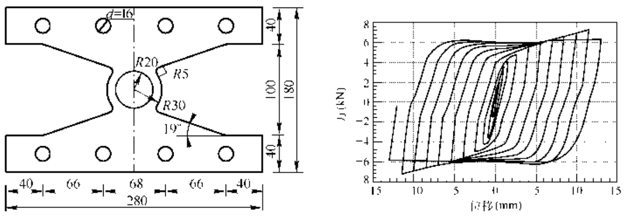

Fig.1 Circle hole type mild steel damper

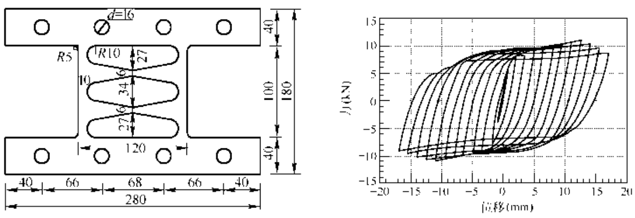

Fig.2 Double X type mild steel damper

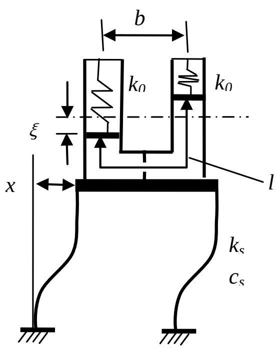

Fig. 3 Illustration of adjustable frequency TLCD

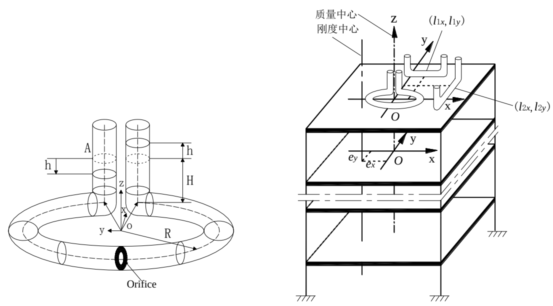

Fig. 4 CTLCD and an eccentric structure with liquid dampers

2.4 *Tuned liquid damper*

TLD are mostly used to reduce the wind induced vibration of structures in engineering. Zhang et al. (1993) carried out shaking table test and verified the vibration control result with TLD subjected to earthquake. Li et al. (1997) presented the multi-modal vibration control of structures using multiple TLDs.

Yan et al. (1998) presented the adjustable frequency tuned liquid column damper by adding springs to the TLCD system, which modified the frequency of TLCD and expended its application ranges (Fig. 3).

To suppress the torsionally coupled responses of structures, Huo and Li (2005) analyzed the control performance of circular tuned liquid damper (CTLCD) (Fig. 4). Subsequently, TLCD and CTLCD are used to control the torsionaly coupled vibration of structures subjected to multi-dimensional earthquake excitation. The optimal parameters of the liquid dampers are designed for the structures excited by bi-directional seismic based on Genetic Algorithms.

3 ACTIVE CONTROL

Active mass damper (AMD) is one of the most common control device employed in full-scale civil engineering. AMD system is designed and installed in the Nanjing Communication Tower in Nanjing, China (Fig. 5). The physical size of the damper was constrained to a ring-shaped floor area with inner and outer radii of 3m and 6.1m, respectively. In addition, the damper was by necessity elevated off the floor on steel supports with Teflon bearings to allow free access to the floor area. The final desing of the active mass damper is shown in Fig. 5.

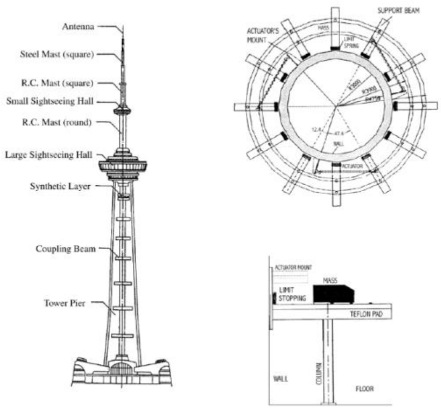

Fig. 5 Nanjing Communication Tower with AMD

4 HYBRID CONTROL AND SEMI-ACTIVE CONTROL

One of the most attractive features of semi-active control systems is that the external energy required for them to operate is usually orders of magnitude smaller than for active systems. The semi-active control system is much more reliable and simple than general active control system, and more effective to reduce the structural response than other passive control system. Examples of semi-active control device include variable orifice fluid dampers, variable stiffness devices, semi-active tuned liquid dampers, controllable friction devices. Li and Liu (1998) carried out the experiments to investigate the behavior of active variable stiffness system. Both of the structural analysis and a small-scaled model shaking table test indicated that the variable stiffness system not only changed frequencies of controller structures but also increased camping ratio. Sun (1998) developed a hydraulic actuator with a controllable orifice. Li et al (2002) experimentally investigated the electromechanical behavior, which is dependent on exciting frequency and applied voltage.

5 STRUCTURAL VIBRATION CONTROL WITH SMART MATERIALS

Smart materials refer to materials that are "responsive". Often the response is the conversion of one form of energy into another in useful quantities. Commonly used smart materials in vibration control include Magneto-rheological (MR) fluids, piezoelectric ceramics and shape memory alloy.

Li (2006) proposed a new MR mechanical model which is called double-sigmoid. The outstanding feature of the proposed model is a fact that magnitude of control current and a wide range of excitation conditions are under consideration. The identification of parameters is relatively easy and the physical concept of the model is obvious through this method.

MR damper was proposed to reduce the torsional response of eccentric buildings. The shaking table experiment of a 2-story frame-shear wall structure model with an asymmetric stiffness distribution was carried out. The experimental results show that the coupled translation and torsion response was significantly mitigated

256 MR dampers with 2.26kN capacity at the cables of the Dongting Lake Cable-stayed Bridge of China to suppress the wind-rain induced dramatic vibration (Ko et al. 2003). 40 MR dampers with 8kN capacity at the cables of Shandong Binzhou Yellow River Highway Bridge (Ou 2003).

The variable friction dampers with a PZT actuator has been proposed by Ou (2003) and other researchers. A new design for piezoelectric friction damper was presented by Li et al (2004).

Shape memory alloys (SMAs) are multi-functional materials due to they have self-sensing, self-actuating and energy dissipation properties. Many researchers focus on developing SMA-based isolators with self-centering performance. Recently, Li et al (2003) developed two selfsensing SMA dampers. The self-sensing SMA dampers have following characteristics: 1) The SMA wires are always elongated during vibration no matter direction of the controlled structure move in; 2) The SMA dampers can self-sense deformation itself, and thus resulting in a potential way to quantificationally assess the safety and damage of the controlled structures post-earthquake hazards; 3)One of SMA dampers can dissipate much more energy because the configuration of the SMA damper with amplifying function deform the SMA wires in the damper larger than the corresponding drift of the controlled structure.

6 CONCLUSIONS

The researches on structural vibration control have made great achievements and some control devices have been applied to practice in recent years in China. However, most researches focus on linear vibration of structures. Studies on control theories for nonlinear systems are still very limited so far and should be paid more attention in the future. Performance based method for all kinds of control systems should be developed to satisfy the engineering requirements. More smart materials and new technologies will be used to control the structural vibration subjected to dynamic load.

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