Recent Research and Application of Earthquake Protection Systems in Taiwan

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ABSTRACT

Research and application of earthquake protection system in Taiwan have become very active since about ten years ago. Many passive control devices, such as triangular steel plates, viscoelastic dampers, viscous dampers, and various forms of seismic isolators, etc., have been studied extensively. These studies have resulted in a few practical applications and proposals of two draft design provisions for seismic isolation design of bridges and buildings. In addition to the pass control, analytical studies on active and semi-active control have also been very active and the experimental studies have been scheduled in the near future. This paper summarise the progress on recent research and application of earthquake protection systems in Taiwan. The emphases are given to the control systems that have been applied in practical applications.

Key words : *earthquake protection system, research activity, practical application*

1. Introduction

Taiwan is in a region with multiple natural hazards such as floods, typhoons and earthquakes. Comparing to typhoon and flood which resulted in economic loss of billions of Taiwan dollars in recent years, damage due to earthquake has been light and scatter in the last twenty years even though moderate and minor earthquakes occur frequently. Two major earthquakes with significant human and economic loss occurred about 50 and 30 years ago in Hsin-Chu and Bai-Ho area, respectively. Because of the frequently occurred earthquakes, people are aware and concerned. Therefore, research and development of earthquake resistant technology have always been a major task for the government, university, and the industry.

Research and application of earthquake protection system in Taiwan have become very active since about ten years ago thanks to very significant investments in experimental facilities in the universities. Many passive control devices, such as triangular steel plates (TADAS),[45] viscoelastic dampers (VED),[3-4, 9-10] viscous dampers,[44] and various forms of seismic isolators[5, 19-21] such as lead rubber bearings, high damping rubber bearings, etc., have been studied extensively. These studies have resulted in a few practical applications. In additions, two draft design provisions for seismic isolation design of bridges and buildings have been proposed.[6, 18] The research activity on earthquake protection system in Taiwan has been intensified recently due to the completion of the experimental facilities in NCREE(National Center for Research on Earthquake Engineering) which include a 5m by 5m, six degrees of freedom shaking table and a reaction wall and strong floor system capable of carrying out full scaled testing of specimens up to 15m high. In addition to

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pass control, analytical studies on active and semi-active control(11-12, 27, 36) of structures have also been very active and the experimental studies have been scheduled using the new shaking table.

This paper summarises the progress on recent research and application of earthquake protection systems in Taiwan. The emphases will be given to the control systems that have been applied in practical applications.

2. Experimental facility

The NCREE Structural laboratory include a state-of-the-art tri-axial seismic shaking table simulator, and a reaction wall and strong floor test system.

The NCREE shaking table is a 5m×5m table with six degrees of freedom(DOF), all of which can be individually programmed. Motion is produced by servocontrolled electrohydraulic actuators. Structural models of up to 50 metric tons can be shaken with a maximum acceleration of 1.0g in the longitudinal direction, 3g in the lateral direction, and 1g in the vertical direction. At less than full load, the maximum accelerations are considerably greater. The system is capable of developing velocities of 60cm/sec in the two horizontal directions and 50cm/sec in the vertical direction. At low frequencies, the system is limited by displacements of 25cm longitudinally, 10cm laterally and 10cm vertically. The analog control system is based on a state-of-the-art, three-variable feedback system. This unique feedback arrangement leads to excellent tracking between the table and the command signal. The frequency limit of the system is determined by the natural frequency of the table and of the supporting oil columns both of which have a natural frequency of approximately 50Hz. This allows operations over a wide band of frequencies with small error. Input or command signals to the table can be of the following types: harmonic motions(sinusoidal, square, triangular), random motions, and any recorded earthquake motion from the library of thousands of recorded accelerograms obtained from various sources. Additional software is available for the collection and processing of system data. Fourier analysis, time analysis, and other on-line procedures can be performed and the results can be electronically stored and either be printed or plotted. Data can also be transferred via the Ethernet to outside systems throughout the world for further processing.

The NCREE reaction wall and strong floor test system consists of a "L-Shaped" box-sectioned reaction wall with step-wise heights of 6m, 9m, 12m, and 15m. The corresponding lengths are 15.5m, 15.5m, 12m and 12m, respectively. The 60m×29m strong floor is 1.2m thick. A wide variety of state-of-the-art transducers, sensing devices, actuators, and data acquisition systems are available.

In addition to NCREE, the reaction wall and strong floor types of structural testing facilities are also available in a few major universities, and two 3m×3m single-degree-of-freedom shaking tables capable of simulating recorded earthquake motions are available in two universities.

3. Base isolation

The technique of base isolation has been extensively applied to decouple the structure from earthquake-induce ground motions for many years. The efficiency and advantage of utilizing base isolation systems in resisting seismic excitations were recently demonstrated in the Los Angeles (1994) earthquake,[14, 17] under which a seven-story hospital (the University of Southern California Teaching Hospital) isolated by lead-rubber bearings was able to keep on operating. In addition, in the great Hanshin earthquake (1995), a building (the Computer Center of the Ministry of Post and Telecommunications) isolated with lead-rubber bearings in the seismic zone survived without any damage or disruption to the operations.[15]

A base isolation system must be able to provide enough horizontal flexibility and additional damping in order to prolong the fundamental periods of the system and at the same time keeping the displacements within acceptable limits. Besides, sufficient rigidity under frequent service loads should be provided by the base isolation system. Among many types of base isolation systems, the elastomeric bearing system, such as natural rubber bearings (NR), lead-rubber bearings, and high damping rubber bearings, is so far the most popular one and has been successfully applied to bridges and buildings for years.[2,22-24,30,32,37-38] In Taiwan, experimental and analytical studies on the lead-rubber bearings combined with energy dissipation devices have been studied extensively.[5,19-21] A typical test setup is shown in Fig. 1. These studies have resulted in domestic productions of lead rubber bearings and high damping rubbers. Typical force-displacement loops of a domestic-made lead-rubber bearing and a high damping rubber bearing are shown in Figs. 2(a) and 2(b), respectively.[20, 21] Fig. 3(a) shows a comparison between a numerical simulation and a shaking table result of a bridge model seismically isolated with natural rubber bearings and viscoelastic dampers (Fig. 3(b)).[5]

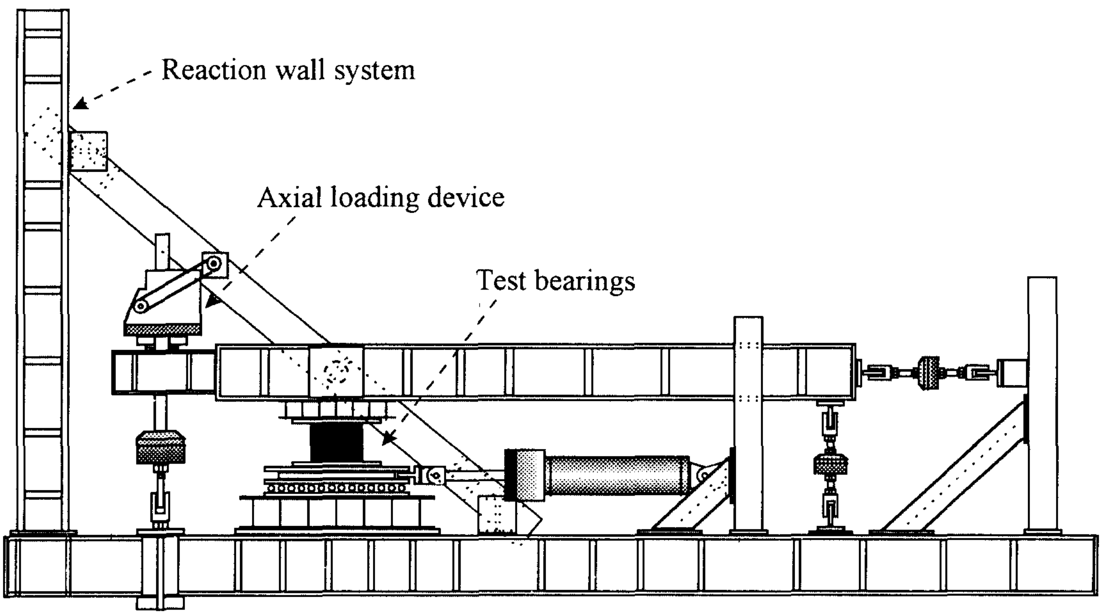

Fig. 1 Typical setup for bearing tests

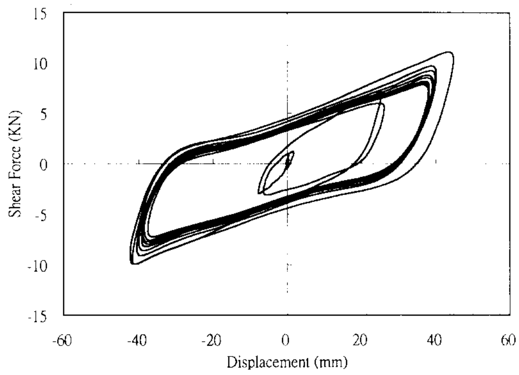

Fig. 2(a) A typical force-displacement loop of a LRB (Strain=40%, Frequency=2.0Hz)

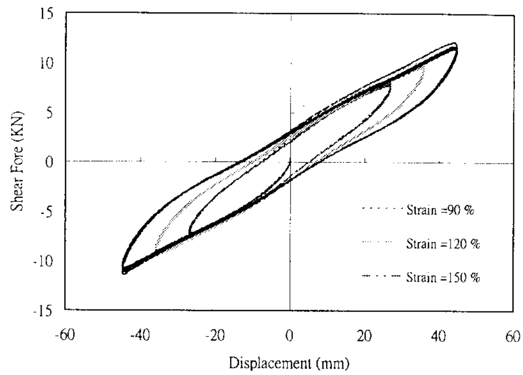

Fig. 2(b) A typical force-displacement loop of a HDR (Vertical load=2.0 tonf, Frequency=1.0Hz)

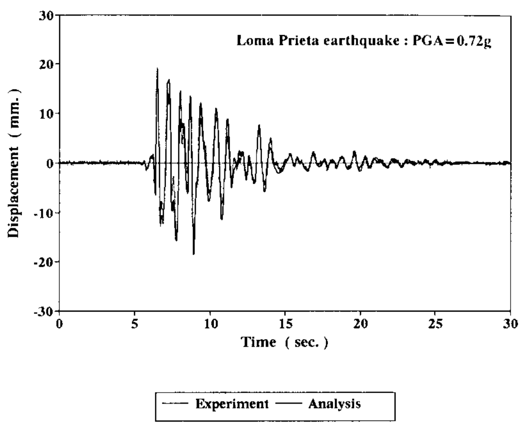

Fig. 3(a) Numerical simulation of RBVD isolated bridge model

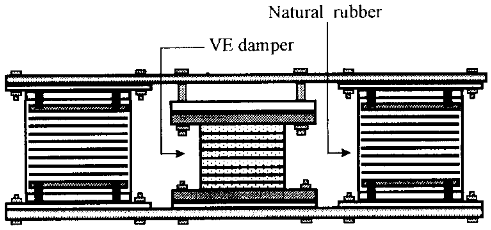

Fig. 3(b) RBVD isolation system

Based on this and other studies, draft provisions for seismic isolation design of buildings and bridges are recently proposed.[6, 18] In addition to the elastomeric types of isolation bearings, there are also analytical studies on sliding types of bearings, which are subjected to experimental studies in the near future.

Practical applications of the seismic isolation system have been applied to eight bridges in the Second Freeway in Taiwan. The adopted isolation system is the lead-rubber bearing system. Because there was no seismic isolation design code available in Taiwan when the bridges were designed, they were designed following the "Guide Specifications for Seismic Isolation Design of Highway Bridges" regulated by AASHTO (1991)[13] and the "Manual for Menshin Design of Highway Bridges" stipulated by PWRI (1992).[29] Fig. 4(a) shows the design drawings of the Bai-ho seismic isolated bridge which is now under construction. Lead-rubber bearings and laminated rubber bearings, as shown in Fig. 4(b), are located at the column piers and the abutments, respec- tively. the overall dimensions of the leadrubber bearings are 1250mm×1250mm in plan and with height of 427mm, as well as that of the laminated rubber bearings are 800mm×600mm in plan and with height of 121mm. Since the Bai-ho bridge is the first

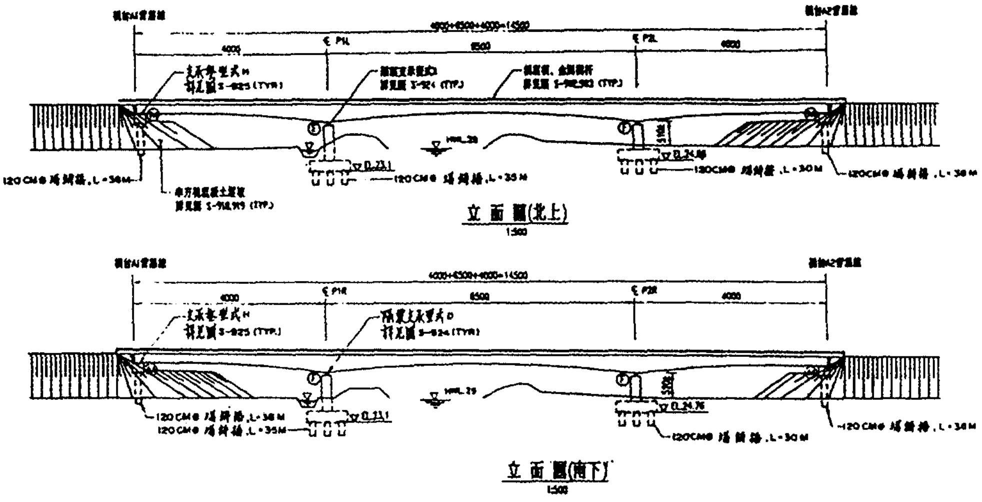

Fig. 4(a) The design drawing of Bai-ho seismically isolated bridge (two ways)

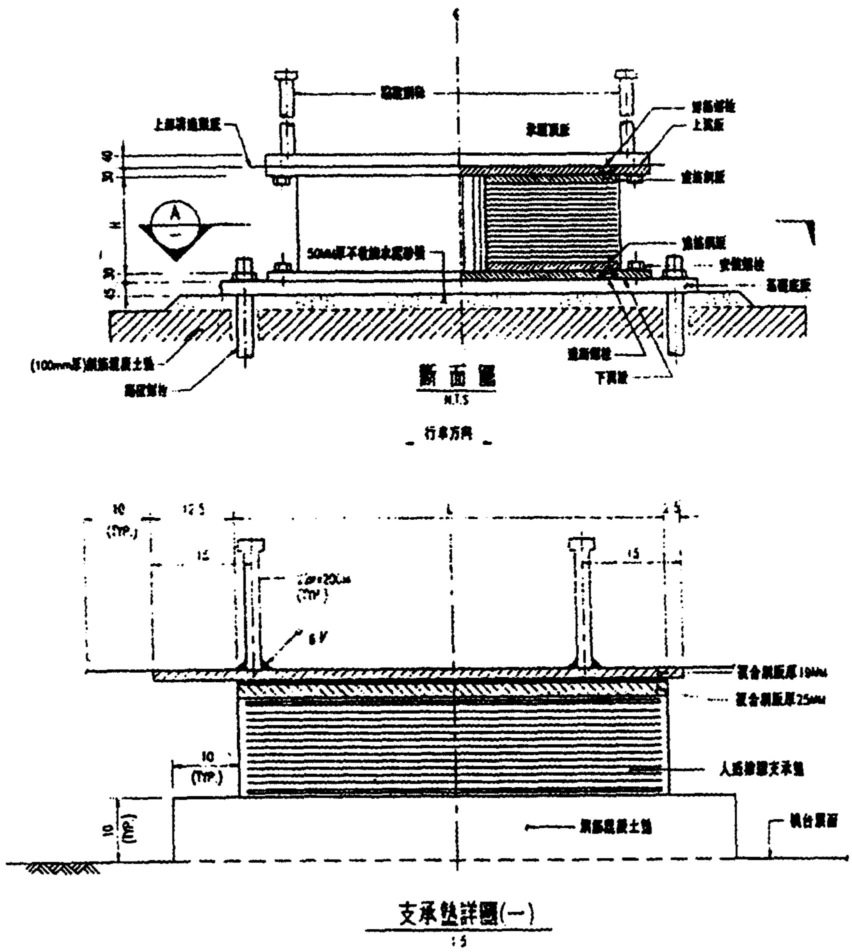

Fig. 4(b) The design drawing of lead-rubber and laminated rubber bearing used in Bai-ho seismically isolated bridge seismically isolated bridge, full scaled tests on this bridge will be carried out once the bridge is completed. In addition to ambient vibration tests, forced vibration tests using vibrators and free vibration tests using hydraulic actuators will be conducted to simulate the bridge response under minor and medium earthquakes. In addition, a seismic monitoring system will be installed to the bridge to measure the response of the bridge under routine traffics and real earthquakes. The results obtained from this study will help promote implementation of seismic isolation technique to bridges in Taiwan.

4. Energy dissipation systems

Comprehensive analytical and experimental studies on the application of energy-absorbing devices, such as metallic dampers, viscous dampers, viscoelastic dampers, and friction dampers, etc., to reduce the dynamic response of structures have been carried out in the past decade.(1,12,42) The earliest practical application of metallic dampers in structures was in New Zealand, where the torsion beam steel damper was used for the piers of the Rangitikei Bridge.(39) Four existing structures, three located in Mexico City(31) and one in California,(35) were retrofitted for seismic resistance by utilizing the ADAS elements. In recent years, the Pall friction devices(33-34) and Sumitomo friction dampers(25) were applied to offer enhanced seismic protection of new and retrofitted structures in Canada and Japan, respectively. For viscous fluid dampers, as an example, the Taylor Devices orificed fluid dampers have been incorporated in many structures for the alleviation of wind and seismic vibrations.(46) In addition, both the tuned mass dampers (TMDs) and tuned liquid dampers (TLDs) have been successfully applied to reduce the wind-induced external loads on high buildings.(26,43) Similar applications of VE dampers were made as early as 1969(28) and the utilization of VE dampers on seismic resistance was took place only recently.(11)

Among the various energy dissipation devices, the viscoelastic (VE) damper is the first one to be applied to a full-scale structure in Taiwan. Taipei MRT Chien-Tan Station adopts a cable-supported roof design to enhance the structural appearance as shown in Fig. 5(a). According to the wind tunnel test results on a 1/120 scaled model, instability of the roof without added VE dampers may occur suddenly after the 70 mph wind speed is reached, which causes the roof to vibrate violently in both vertical and torsional modes. Also, from the test results, the inherent damping ratios of the model were observed to be 0.6% for the vertical and 1% for the torsional mode, respectively. The VE dampers should be designed so that the structure has at least 8% damping ratio for the vertical and 4% for the torsional mode to stabilize the roof. Thus, eight VE dampers were installed on the Taipei MRT Chien-Tan Station to dissipate the excessive vibrational energy built-up in the cable-supported roof of the station through providing additional damping of 7.4% for the vertical and 3% for the torsional mode. Each damper consists of two sub-dampers in series to fit into the light post of the station as shown in Fig. 5(b). Recently, a monitoring system for wind and earthquake is installed to the station(Fig. 6). In addition to 32 channels of accelerometers, six propeller

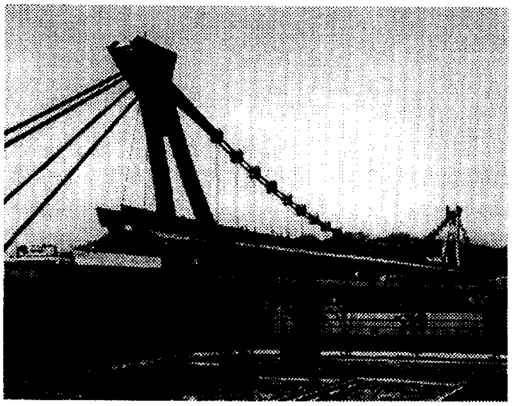

Fig. 5(a) Taipei MRT Chien Tan Station

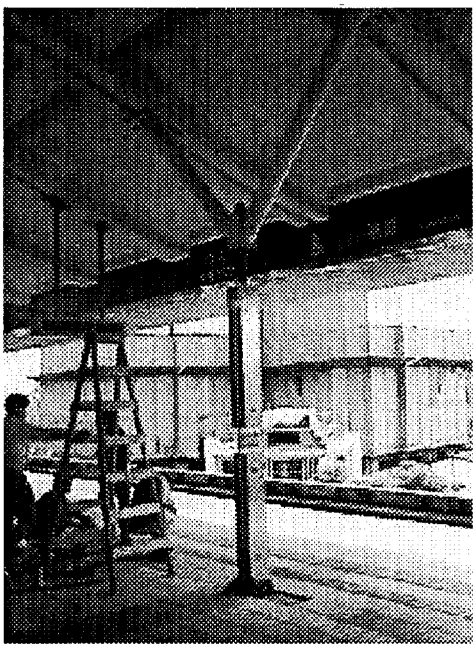

Fig. 5(b) VE dampers used in Taipei MRT Chien Tan Station

anemometers are installed on the roof for wind speed measurements, four displacement meters and two thermocouples are installed in the dampers to measure the damper displacement and damper tempera- ture.

The National Center for Research on Earth- quake Engineering (NCREE) of Taiwan has

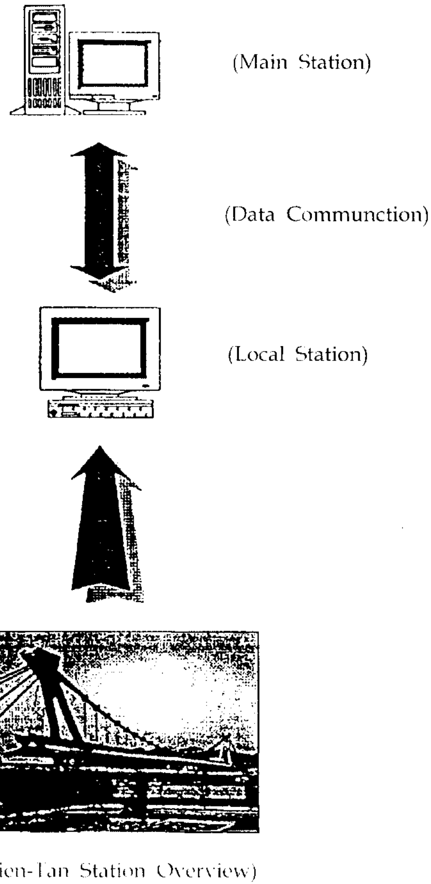

Fig. 6 MRT Chien-Tan Station monitoring system schematic diagram

also constructed and instrumented two full- scaled five-story steel buildings in I-Lan, a city located 80km south-eastern away from Taipei city where sizable earthquakes occurred frequently, for the purpose of investigating the dynamic behavior of struc- tural control devices for seismic hazard mitigation. Two types of VE dampers were installed to one building with one type for each direction and tapered ADAS(TADAS) elements were installed to the other building. Fig. 7 presents both the frames with added energy dissipation devices on them. Ambient and free vibration tests at various environmental temperatures and weather conditions were carried out routinely, and seismic responses of the steel frame with added dampers were recorded and analyzed.[8] A typical seismic response of the structure with added VE dampers recorded on March 5, 1996 is shown in Fig. 8.

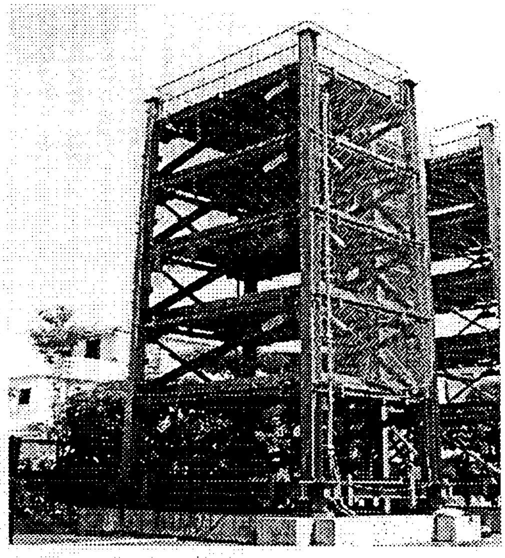

Fig. 7 I-Lan five-story full-scaled steel frame

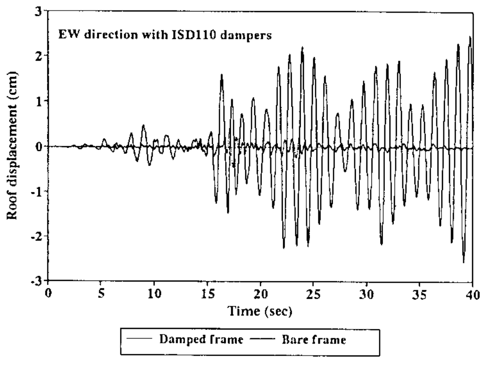

Fig. 8 A typical seismic response of the I-Lan steel building with added VE dampers

In addition to viscoelastic dampers, the triangular steel plates with added damping and stiffness (TADAS) are also subjected to extensive studies. Results of the studies show that these devices can be effective to sustain many large inelastic cycles of deformation.[45] Full-scale steel frames with added TADAS were also tested by pseudodynamic test method to demonstrate the effectiveness of this device under major earthquakes.

5. Active control systems

Comparing to the passive control technology, the active and semi-active structural control, in which the motion of a structure is controlled or modified by means of the action of a control system through some external power supply, has a more recent origin.[16, 40-41, 48-49] Over the past 20 years, considerable efforts have been made on the researches and developments of many feasible active control mechanisms, such as active bracing system(ABS), active mass damper (AMD), and variable stiffness systems etc., and control theories, such as stochastic control, optimal control, and instantaneous optimal control etc., and control theories, such as stochastic control, optimal control, and instantaneous optimal control etc. There are now more than 20 active or hybrid control devices installed in large civil structures and nearly all of them are constructed in Japan. The first application of active control system to a real building was carried out by the Kajima Corporation in 1989.[25] An AMD system, composed of two AMDs, was installed on the 11-story Kyobashi Seiwa building to reduce the vibrations under strong winds and minor earthquake excitations such that the comfort of the occupants in the building can be increased. In addition, the hybrid mass damper(HMD), which is a combination of a TMD and an active control actuator, is the most common control device applied to full-scale structures. For example, an arch-shaped HMD was employed in the bridge tower of the Rainbow suspension bridge in Tokyo to reduce vortex-induced vibration and two multistep pendulum HMDs were installed in the Yokohama Landmark Tower,[48] which is the tallest building in Japan. These devices performed well to control the motions induced by wind loads and minor earthquake excitations.

In Taiwan, the first practical application of active control devices was initiated in 1994. Two sets of tuned active damper (TAD) were installed at the 78th story of the 85-story T&C Tower Building, currently the

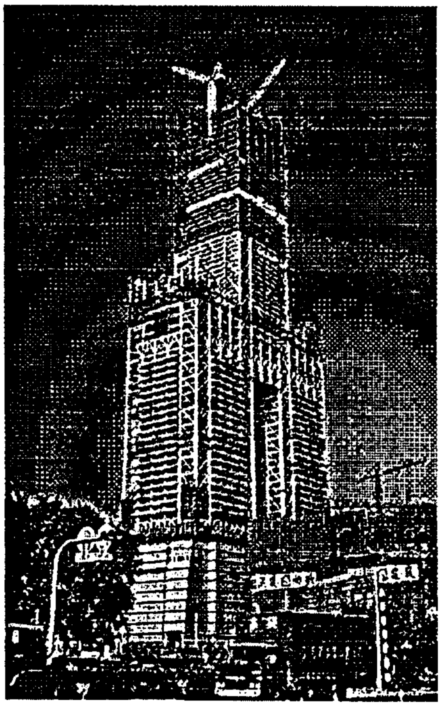

Fig. 9(a) Elevation view of T&C Tower Building

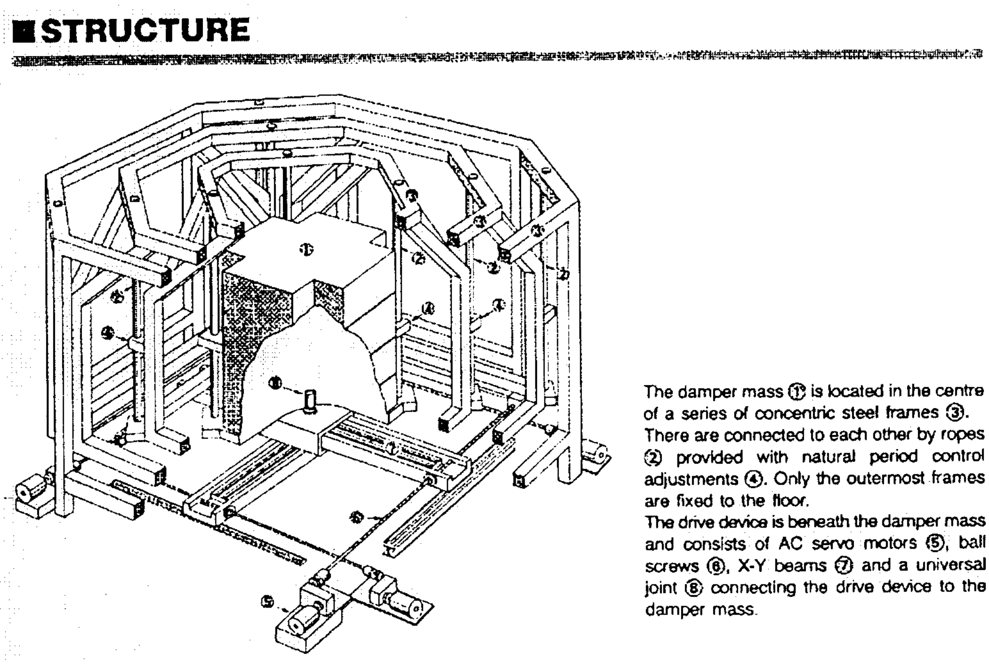

Fig. 9(b) Outlines of tuned active damper(TAD) tallest building in Taiwan with the height of 347.6 meter above ground, to reduce the floor acceleration due to wind. Fig. 9(a) and 9(b) show the elevation view of the tower and the outlines of the TAD. The two TADs were designed to provide 8% additional damping when the TADs are in operation and to withstand a 100-year recurrent wind velocity under strong wind conditions. Velocity meters are used to obtain the displacements and velocities of the building and the TAD mass. The acceleration signals differentiated from the velocity signals are used to start and stop the TAD and for the erroneous operation detection system. From the results of a preliminary analysis, under the 0.5-year recurrent wind velocity, the response of the structure is reduced down to about 45% of that without TADs in both the peak and root-mean-square values. Moreover, when the wind speed increases, the structural response is reduced further down to about 50% and 60% of that without TADs under the 25-year and 100-year recurrent wind, respectively.

The active control technique has been limited to analytical and numerical development[9-10, 27] in Taiwan. With the completion of the NCREE shaking table, experimental studies are scheduled in the near future.

6. Summary

The development of earthquake protection system has been a major interest in Taiwan during the past decade. The extensive research has resulted in a few practical applications and two draft design provisions for bridges and buildings. With the completion of the test facility in NCREE, it is expected that the research and application of earthquake protection in Taiwan will be intensified.

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