A REVIEW ON STRUCTURAL CONTROL OF SEISMICALLY AND WIND EXCITED STRUCTURES

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Abstract*—In recent years, considerable attention has been paid to research and development of passive and active structural control devices, with particular emphasis on alleviation of wind and seismic response of buildings and bridges. In both areas, serious efforts have been undertaken to develop the structural control concept into a workable technology, and today we have many such devices installed in a wide variety of structures.Structural control is the control of structural vibrations produced by earthquake or wind or any other dynamic loading. Structural control is basically the modification of the properties of a structure in order to achieve a structurally desirable response to a given external load. Structural control can be done by various means such as modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces.This review paper deals with the structural control of seismically and wind excited structure and elaborate the controls by structures to the building. The purpose of structural control is to absorb and to reflect the energy introduced by dynamic loads such as winds, waves, earthquake, and traffic. Today, the protection of civil structures from severe dynamic loading is typically achieved by allowing the structures to be damaged.

***Index Terms*—Wind Excited Structure, Seismically Structure, Structural Control**

I. Introduction

Civil engineering structures located in environments where earthquakes or large wind forces are common will be subjected to serious vibrations during their lifetime. These vibrations can range from harmless to severe with the later resulting in serious structural damage and potential structural failure. The traditional method of antiseismic technique is to increase the stiffness of structures by enlarging the section of columns, beams, shear walls, or other elements, which will enhance the seismic load because of the added mass to structures. As a result, although the cost of structures with traditional antiseismic technique is increased a lot, the safety level of structures is less improved. Another disadvantage of the traditional antiseismic technique is that it focuses on the protection of the structure but neglects the facilities inside the structure. Hence, it cannot be used in some structures whose facilities inside them are very important, such as hospitals, city lifeline engineering, nuclear plants, museum buildings, and the buildings with precise instruments.

Design for strength alone does not necessarily ensure that the building will respond dynamically in such a way that the comfort and safety of the occupants is maintained. For example, during the 1989 Loma Prieta earthquake, a 47-story building in San Francisco experienced peak accelerations of about l0% g in the basement and 45%g on the top floor, which indicates that harmful accelerations in the upper stories can result from strong ground accelerations. Similar comments can be made regarding the behavior of structures during the recent Northridge and Kobe earthquakes. In fact, the requirements for strength and for safety can be conflicting. Thus, alternate means of increasing the resistance of a structure while maintaining desirable dynamic properties, based on the use of various structural control schemes, offers great promise.

Another method of antiseismic technique is structural control. Structural control is basically the modification of the properties of a structure, such as a building or bridge, in order to achieve a structurally desirable response to a given external load. The modification of the structure’s properties includes changes in the damping and stiffness of the structure, so that it can respond more favorably to the external loading. Structural control is most typically employed in cases involving dynamic loads, so that the potential exists for modification of the structure’s properties to permit a reduction in the level of excitation transmitted to the structure. Although the concept of structural control is appealing and exciting, the basic concepts of structural control themselves are not new. They have been the staple of electrical and control engineering for decades, and have been applied successfully in a variety of disciplines, such as aerospace and mechanical engineering. However, structural control of civil engineering structures has a more recent origin, and its application to civil engineering structures is unique and presents a host of new challenges, especially for reducing earthquake structural responses, because of the uncertainties and the mighty power of earthquake forces.

The notion of structural control as currently defined can trace its roots back more than 100 years to John Milne, a professor of engineering in Japan, who built a small house of wood and placed it on ball bearings to demonstrate that a structure could be isolated from earthquake shaking.

However, structural control systems in reality existed several centuries earlier in Japan, due to an unknown engineer. They were applied to the construction of a Gojunoto (pagoda). The pagoda was five stories tall and was constructed of closely fitting, mortised wooden beams and columns. During an earthquake, the vibrations of such a vertical cantilever structure would produce bending moments that could not be resisted by tension at the mortised joints. To overcome this weakness, a long wooden pole was suspended freely from the upper part of the pagoda to act as a pendulum if the pagoda were excited into motion by an earthquake. The weight of the pole exerted a compressive prestress on the pagoda, thus increasing the bending resistance. The bottom of the pole extended into a cylindrical hole in the ground that was of larger diameter than the pole. Thus, when the pagoda was excited into vibrations by an earthquake, some of the vibrational energy would be transferred into oscillations of the pole, and the impact of the pole on the sides of the hole would dissipate energy.

II. Structural Control

Structural control is the control of structural vibrations produced by earthquake or wind or any other dynamic loading. Structural control is basically the modification of the properties of a structure in order to achieve a structurally desirable response to a given external load. Structural control can be done by various means such as modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces.

The purpose of structural control is to absorb and to reflect the energy introduced by dynamic loads such as winds, waves, earthquake, and traffic. Today, the protection of civil structures from severe dynamic loading is typically achieved by allowing the structures to be damaged. Consider the conservation of energy relationship proposed by Uang and Bertero (1988)-

$$E = E_k + E_s + E_h + E_d \qquad \text{……………………………..(Eq. 1)}$$

Where: E is the energy induced by seismic shaking; Ek is the kinetic energy; Es is the elastic strain energy; Eh is the energy dissipated by the structural system due to inelastic deformation; Ed is the energy dissipated by supplemental damping devices. By including the energy term Ed through structural control, the energy dissipated by supplemental damping devices, the kinetic, elastic, and, most importantly, the inelastic deformation energy can be reduced, preserving the primary structure.

Passive Control

A passive control system may be defined as a system which does not require an external power source for operation and utilizes the motion of the structure to develop the control forces. Control forces are developed as a function of the response of the structure at the location of the passive control system. The relative motion of the mechanism defines the amplitude and the direction of the controlling force. Systems in this category are very reliable since they are unaffected by power outages, which are common during earthquakes. They dissipate energy using the structure's own motion to produce relative movement within the control device (Symans et al. 1994) or by converting kinetic energy to heat. Since they do not inject energy into the system, they are unable to destabilize the structure. Another advantage of such devices is their low maintenance requirements.

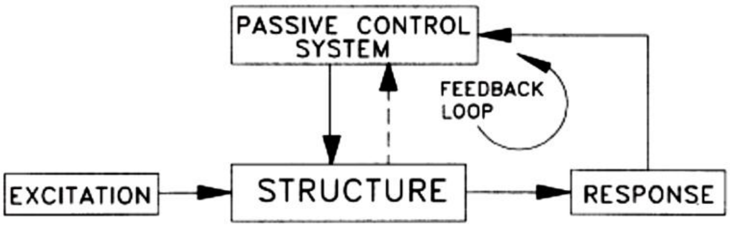

Figure 1 Passive Control System

From energetical point of view the passive control system are divided into two classes as seismic Base Isolation and Passive Energy Dissipation (PED).

Active Control

Active control method is affected by externally activated device, to change the response. The activation of external force is based on the measurement of external disturbance and/or structural response. Sensors are employed for the measurement purposes, and with the help of computers, the digital signal activates (converted to analog signal) the required external force. Active control systems are reaction based real time force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. These act simultaneously with the hazardous excitation to provide balancing force mechanism and thereby enhanced structural behaviour for improved service and safety. Schematically such systems may be presented in Figure 2.

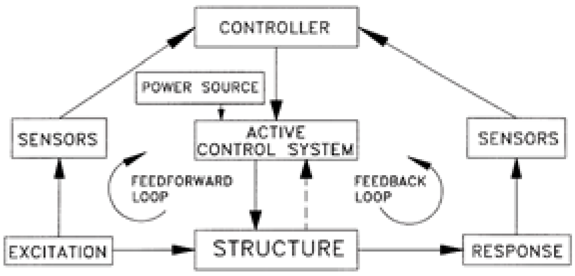

Figure 2 Active Control System

Such systems are used to control the response of structures to internal or external excitation, such as machinery or traffic noise, wind, or earthquakes, where the safety or comfort level of the occupants is of concern. Active control makes use of a wide variety of actuators, including active mass dampers, hybrid mass dampers, tendon controls, which may employ hydraulic, pneumatic, electromagnetic, or motor driven ball-screw actuation. An essential feature of active control systems is that external power is used to effect the control action. This makes such systems vulnerable to power failure, which is always a possibility during a strong earthquake.

The control forces within an active control system are typically generated by electro hydraulic or electromechanical actuators based on feedback information from the measured response of the structure and/or feed forward information from the external excitation. The recorded measurements from the response and/or excitation are monitored by a controller (a computer) which, based on a pre-determined control algorithm, determines the appropriate control signal for operation of the actuators. The generation of control forces by electro hydraulic actuators requires large power sources, which are on the order of tens of kilowatts for small structures and may reach several megawatts for large structures.

Hybrid Control

Any one type of control system may not be most effective measure in all types of dynamic loading conditions. Hence, applying more than one type of structural control methodology to the structures is thought to be more effective. In this concept, a combination of more than one type of systems acts simultaneously to restrict the structural response. Active, Passive and Semi-Active devices can be combined in various combinations, resulting in Hybrid Control system. Schematically, such systems may be presented as in Figure 3.

Because multiple control devices are operating, hybrid control systems can alleviate some of the restrictions and limitations that exist when each system is acting alone. Thus, higher levels of performance may be achievable. Additionally, the resulting hybrid control system can be more reliable than a fully active system, although it is also often somewhat more complicated.

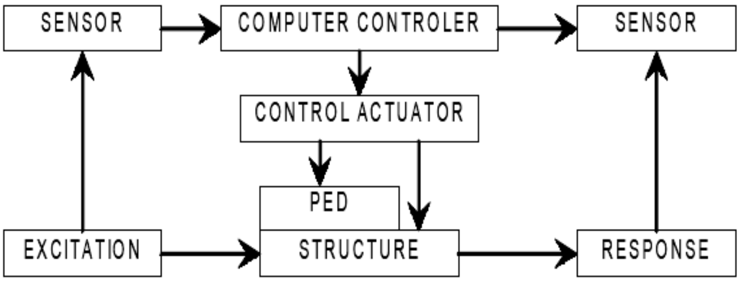

Figure 3 Hybrid Control System

III. CONTROLLED STRUCTURE: FEW EXAMPLES

In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on alleviation of wind and seismic response of buildings, bridges and other structures. In all areas, serious efforts have been undertaken to develop the structural control concept into a workable technology, and today we have many such devices installed in a wide variety of structures.

As alluded to earlier, the development of active, hybrid, and semi-active control systems has reached the stage of full-scale applications to actual structures. Most of these full-scale systems have been subjected to actual wind forces and ground motions and their observed performances provide invaluable information in terms of -

(a) Validating analytical and simulation procedures used to predict actual system performance,
(b) Verifying complex electronic-digital-servohydraulic systems under actual loading conditions, and
(c) Verifying capability of these systems to operate or shutdown under prescribed conditions.

Buildings

High-rise buildings have to receive special treatment at the design stage. Ordinary seismic design codes and guidelines do not apply to such structures. Less design base shear can be employed by taking into account the dynamic characteristics of structures, which are likely to be more flexible structures with a relatively long natural period. As a building gets higher, on the other hand, wind loads are likely to become larger. Therefore, high-rise buildings may have poor performance and serviceability during strong winds, even though safety is not endangered, resulting in the buildings occupants feeling uncomfortable. With the implementation of structural control, whether it is of the passive or active type, high-rise buildings may have better performance and serviceability.

Taipei Financial Center or Taipei 101 Tower (Taipei, Taiwan)

One example of the applications of TMDs system can be found at the Taipei Financial Center also known as Taipei 101 Tower which is in the capital city Taipei, Taiwan as shown in Figure 1. Its height is 508 meters which is the tallest building in the world. The mass of TMD pendulum type is 660 tons as shown in Figure 1 and the mass of two TMDs pinnacle type weighs 4.5 tons each which were installed in 2002.

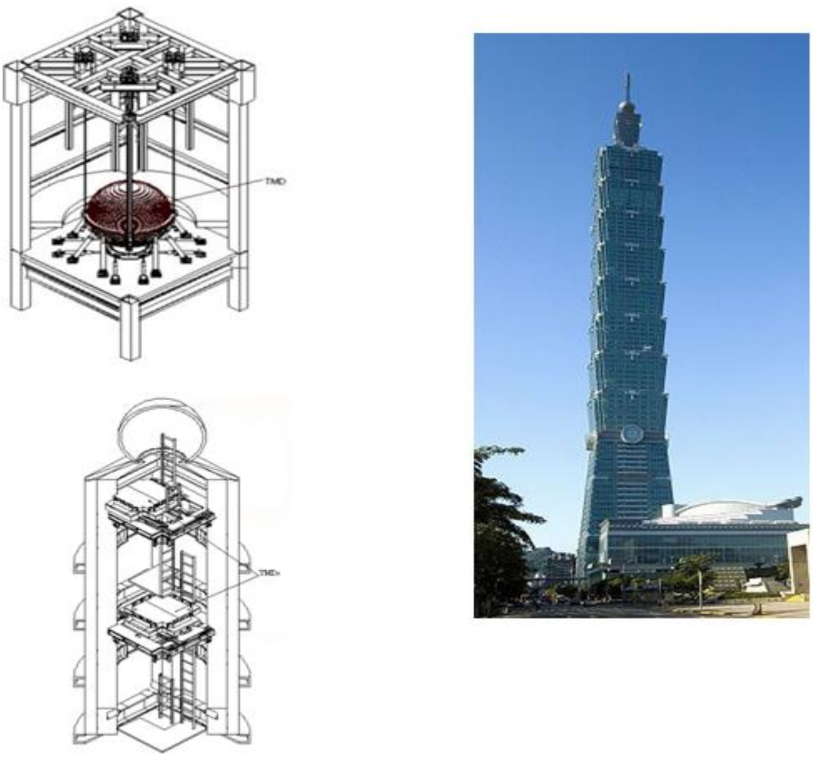

Figure 1 Taipei 101 Tower and TMD

One Wall Centre (Vancouver, BC, Canada)

One example of application of TLCDs system can be found in One Wall Centre in Vancouver, BC, Canada as shown in Figure 2. Its cross-section is illustrated in Figure 2 as a wide elliptical footprint with a 7:1 slenderness ratio. Two Tuned Liquid Column Dampers were installed to control wind-induced vibrations. Each TLCD contains 230 tons of water tuned to the proper frequencies. The benefits of using a TLCD to reduce motions of a building can be threefold. Firstly, the building acceleration responses due to wind can be reduced. Secondary, the water in the tank can be used for firefighting or chilled water storage. Thirdly, the construction costs and maintenance costs are much lower compared to conventional damping systems.

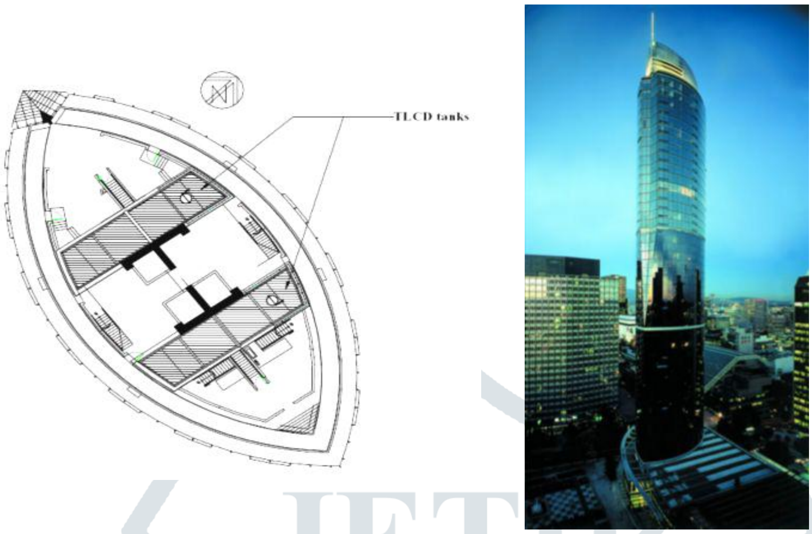

Figure 2 One Wall Centre and Cross-sections of One Wall Centre

The Kajima Technical Research Institute

The Kajima Technical Research Institute, shown in Figure 3, was the first full-scale building structure to be implemented with semi-active control devices. The AVS is a hydraulic device with a bypass valve used to switch the device between the on-off positions to engage and disengage the bracing system. Thus, the structural system varies between the configurations of a purely moment resistant framing system to a fully braced framing system. The building's stiffness is varied based on the nature of the earthquake to produce a non resonant system. The observed responses during several earthquakes Kobori et al. 1993 indicate the effectiveness of the AVS system in reducing the structural responses.

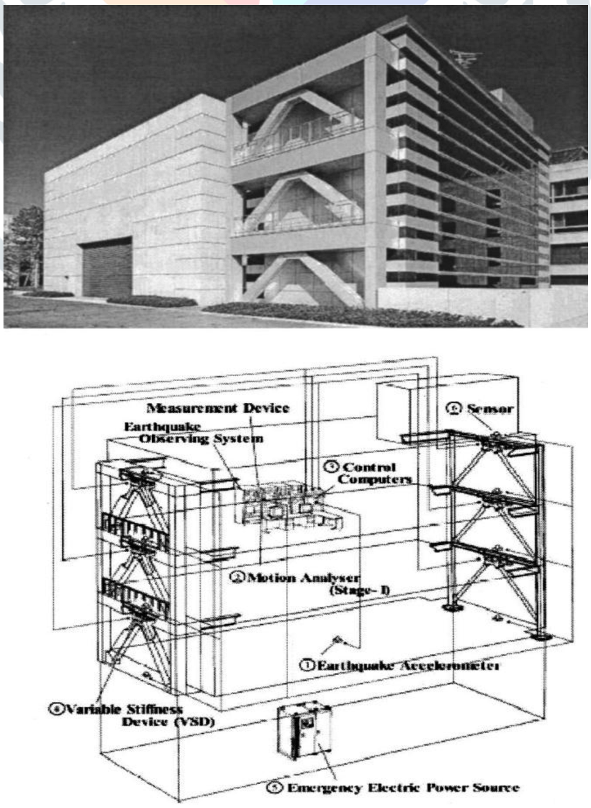

Figure 3 Kajima Technical Research Institute with AVS system

Bridges

The issue of energy dissipation becomes even more acute for bridge structures because most bridges, especially long-span bridges, possess very low inherent damping, usually less than 5% of critical. When these structures are subjected to strong earthquake motions, excessive deformations can occur by relying on only inherent damping and inelastic deformation. For bridges designed mainly for gravity and service loads, excessive deformation leads to severe damage or even collapse. In the instances of major bridge crossings, as was the case of the San

Francisco–Oakland Bay Bridge during the 1989 Loma Prieta earthquake, even non collapsing structural damage may cause very costly disruption to traffic on major transportation arteries and is simply unacceptable.

Other alternatives, for bridge design, include installing isolators to isolate seismic ground motions or adding passive energy dissipation devices to dissipate vibration energy and reduce dynamic responses. The successful application of these new design strategies in bridge structures has offered great promise. In comparison with passive energy dissipation, research, development, and implementation of active control technology has a more recent origin. Since an active control system can provide more control authority and adaptivity than a passive system, the possibility of using active control systems in bridge engineering has received considerable attention in recent years.

Kwangan Bridge (Pusan, Korea)

An approach section of the Kwangan Bridge in Pusan, which is a suspension bridge under construction with the center span length of 500 m, is the first base-isolated bridge in Korea (Kim, 1998). The bridge and base isolators using LRB are illustrated in Figure 4. It is a continuous double deck truss section with 3 spans. The length of each span is 120m. Because of the heavy weight of the truss section, it is natural to adopt seismic isolation system for effective seismic design of piers. It was designed for the earthquake load with a PGA of 0.14g. The design effective natural period is 1.82 sec. The earthquake responses were evaluated in the longitudinal direction for various levels of the earthquake excitation.

Figure 4 Kwangan Bridge with Lead Rubber Bearing

Dangsan Railway Bridge (Seoul, Korea)

Dangsan railway bridge spanning Han River in Seoul was a steel truss bridge completed in 1983 (Figure 5 a). It had 15 spans with the each span length of 90m. This bridge was used for Seoul Subway Lane 2, and its importance was unquestionable. In 1992, however, train speed was limited to 30km/h on the bridge because several cracks were found in major truss members. In 1996, Seoul City Government decided to replace the superstructure of the bridge. For the rehabilitation, it was necessary to increase seismic capacity of the bridge due to seismic code revision in 1992. As an economical design alternative, reuse of foundations, retrofit of concrete piers and seismic isolation system was chosen. New steel box superstructure with isolator system was completed in 1999 (Figure 5 b).

(a) Old bridge (b) New bridge

Figure 5 Dangsan Railway Bridge

Liquid Retaining Structures

Liquid storage tanks are lifeline structures and strategically very important, since they have vital use in industries and nuclear power plants. Unlike most structures (such as buildings or bridges), the weight of storage tanks varies in time because of variable liquid storage level, and they may contain low-temperature (e.g., LNG) or corrosive substances. Recent years have seen a number of occurrences of catastrophic failures of liquid storage tanks due to severe, impulsive, seismic events such as the 1994 Northridge earthquake in California, the 1995 Kobe earthquake in Japan and 1999 Chi-Chi earthquake in Taiwan. Failure of storage tanks not only instantly disrupts essential infrastructure but can also cause fires or environmental contamination when flammable materials or hazardous chemicals leak. Consequently, protection of liquid storage tanks against severe seismic events has become crucial.

The earthquake motion excites the liquid contained in the tank. A part of the liquid moves independent of tank wall motion, which is termed as sloshing, while another part of the liquid which moves in unison with the rigid tank wall is known as impulsive mass. If the flexibility of the tank wall is considered then the part of the impulsive mass moves independently while the remaining accelerates back and forth with the tank wall known as rigid mass. The accelerating liquid, sloshing, impulsive and rigid masses, induces substantial hydrodynamic pressures on the shell wall of liquid storage tanks which in turn generates lateral pressures (i.e. base shear) and overturning moment. The overturning moment produces excessive compressive stresses at the bottom of one side of the tank. The excessive stresses induce buckling of the shell of the tank wall. The failure of liquid storage tanks is mainly due to buckling of the tank wall, failure of piping system and uplift of the anchorage system. The seismic behaviour of liquid storage tank is highly complex due to liquid–structure interaction leading to a tedious design procedure from an earthquake-resistant design point of view. Housner (1957, 1963) developed lumped mass model of ground supported liquid storage tank with two-degrees-of-freedom (i.e. associated with convective mass and impulsive mass) to investigate the seismic response. It is observed that the liquid pressure generated due to earthquake ground motion is very important for seismic design of the tanks. Rosenblueth and Newmark (1971) modified the expression suggested by Housner (1963) to estimate the convective and impulsive mass to evaluate the seismic design forces of liquid storage tanks. Epstein (1976) has suggested closed form expressions to calculate lumped masses to find seismic response of liquid storage tanks. Haroun (1983) developed design charts to estimate convective, impulsive and rigid masses, assuming the liquid contained in the tank as incompressible with irrotational flow.

Pilot LNG tank (Korea)

The Korea Gas Corporation and the Korea Gas Eng. & Cons. Co., Ltd. are constructing the Pilot LNG tank system for their new commercial tank system with their own developed membrane system. Because the LNG tanks are often constructed on the flexible foundation as compared to other safety-related structures, seismic isolators are introduced to reduce the earthquake stresses on the tank structure due to the effect of flexible foundation. The study on optimal isolator design for the new tank system on flexible foundation is being performed by Korea Power Engineering Company. Fig.ure 6 shows a view of the pilot LNG tank in which the seismic isolators are placed on top of pedestals, which are supported by a thick concrete foundation slab on piles. The pilot LNG tank structure is approximately 1/4 scale of commercial tank system, but some geometrical dimensions such as wall thickness could not reduced by the same scale, i.e. these are relatively thicker than others. The properties of isolator were adjusted with seismic analysis changing seismic isolator characteristics.

Figure 6 Pilot LNG tank

IV. CONCLUSIONS

It has been understood that structural control is utilized either to reduce the amount of energy transfer into the structure from the ground motion or to absorb some of the earthquake energy after it has been transmitted to the structure. Passive control systems whose properties cannot be modified after installation and require no external power or computer process for their operation. Active control systems utilize actuators to apply control forces to the structure, which are determined by incorporating the actuators within a feedback control system that utilizes the measured response of the structure or the measured ground motion feedback. Semi-active systems may be regarded as passive control systems, which have been modified to allow for the adjustment of their mechanical properties. Finally, hybrid systems consist of combinations of the aforementioned control systems. Active, semi-active and hybrid structural control systems are a natural evolution of passive control technologies such as base isolation and passive energy dissipation. The possible use of active control systems and some combinations of passive and active systems, so called hybrid systems, as a means of structural protection against wind and seismic loads has received considerable attention in recent years. Active/hybrid control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. They act simultaneously with the hazardous excitation to provide enhanced structural behavior for improved service and safety.

For the last thirty years or so, the reduction of structural response caused by dynamic effects has become a subject of intensive research. Many structural control concepts have been evolved for this purpose, and quite a few of them have been implemented in practice. There are a number of motivating factors for conducting this research. They include: (i) reduction of undesirable vibrational levels of flexible structures due to unexpected large environmental loads; (ii) retrofitting existing structures against environmental hazards; (iii) protecting seismic equipments and important secondary systems; and finally, (iv) providing new concepts of design of structures against environmental loading.

There are a number of mechanisms by which the structural control action is achieved. For example, in the category of passive control base isolation devices, visco-elastic dampers, tuned mass dampers, liquid column dampers, liquid-mass dampers, metallic yield dampers, and friction dampers have been proposed. Out of these, base isolation devices have been widely implemented in practice. In active control, active mass/tuned mass dampers (ATMD), active tendon systems, actuators/controllers have been used. Out of these, active mass/tuned mass dampers have been implemented for the response reduction of tall buildings in controlling wind-induced vibrations. In hybrid control, the concepts using base isolation and ATMD, and visco-elastic dampers and ATMD have been proposed. In semi-active control, Electrorheological/ Magnetorheological dampers, fluid viscous dampers, and tuned mass dampers are being investigated.

REFERENCES

[1] Baker, G.A., Johnson, E.A., Spencer Jr., B.F. and Fujino, Y. (1999), "Modeling and semiactive damping of tay cables", Proc.13th ASCE Engrg. Mech. Conf., Baltimore, Maryland, 6 pages (CD-ROM).
[2] Carlson, J.D. and Spencer Jr., B.F. (1996), "Magneto-rheological fluid dampers for semi-active seismic control",
[3] Proc. 3rd Int. Conf. on Motion and Vib. Control, Chiba Japan, III, pp35-40.
[4] Carlson, J.D. and Weiss, K.D. (1994), "A growing attraction to magnetic fluids", Machine Design, pp61-64.
[5] Ayyub B.M. (Eds.) "Uncertainty modeling and analysis in civil engineering", CRC Press, 1997.
[6] Housner, G.W., L.A. Bergman, et. al, "Structural Control: Past, Present, and Future", ASCE Journal of Engineering Mechanics, 1997; 123(9): 897-971.

[7] Kobori, T., M. Takahashi, T. Nasu, N. Niwa, and K. Ogasawara, "Seismic Response Controlled Structure with Active Variable Stiffness System", Earthquake Engineering and Structural Dynamics, 1993, 22, 925-941.
[8] Pedrycz, W., "Fuzzy control and fuzzy systems", Wiley, New York, 1993
[9] SIMULINK, The Math Works, Inc. Natick, Massachusetts, 2002.
[10] Soong, T.T., S.F. Masri and G.W. Housner, "An overview of active structural control under seismic loads" Earthquake Spectra, 1991; 7: 483-505.
[11] Spencer, Jr., B.F., S.J. Dyke and H.S. Deoskar, "Benchmark Problems in Structural Control, Part I: Active Mass Driver System, Earthquake Engineering and Structural Dynamics, 1998, 27(11): 1265- 1269.
[12] Yao, J.T.P., "Concept of structural control", ASCE Journal of the Structural Division, 1972, 98(7): 1567-1574.