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# RECENT ACTIVITIES IN RESEARCH AND APPLICATION OF STRUCTURAL CONTROL AND MONITORING SYSTEMS IN KOREA

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## SUMMARY

Although the seismic hazard in Korea has been considered to be low, need for structural control and monitoring systems has grown rapidly due to increasing recognition of the risk against natural hazards and growing number of constructions for large structures. The present paper describes recent activities in structural control research and application in Korea. From early passive seismic protection system to recent active control system, several technologies that have been actively researched in Korea since the early 1990's are reviewed. The activities of the Korea Panel on Structural Control and Monitoring are also introduced.


## INTRODUCTION

Research and application of structural control and monitoring in Korea have become active since the early 1990's partly because of deteriorating infrastructure systems mostly built in the rapidly industrialized period of 1970's, and partly because of increasing recognition of the risk due to natural hazards such as typhoons and earthquakes. Earlier activities were researches on the application of passive seismic protection systems to nuclear related facilities that are subjected to most stringent seismic safety requirements. For civil structures, there had been more concern on the control of vibration due to wind and other man-made actions because of low seismic risk in the country. However, due to recent evidences of increasing seismic activities in Korea[Lee and Noh 1988] and lessons learned from the Northridge and Kobe earthquakes, the recognition of potential devastating disruption of industrial and infrastructure systems which the economy of Korea is so much relying on has aroused. Accordingly, seismic performance requirements for civil and industrial structures have been strengthened, which prompted systematic works on the research and application of structural control techniques.

Current studies on seismic protection systems mostly concern the development and application of seismic isolators such as lead rubber bearings and high damping rubber bearings, viscoelastic dampers and viscous dampers. Active and hybrid vibration control systems are also actively studied mainly for long-span bridges and high-rise structures against wind actions. Control algorithms considering various practical design limitations have been studied and actually applied to an air traffic control tower in Inchon International Airport under construction, the first structure equipped with hybrid vibration control system in Korea. Development of system identification and monitoring techniques is also active mainly for the application to bridge structures. These activities are mostly performed jointly by industries, universities and research institutes. Among them, the Korea Earthquake Engineering Research Center supported by the Korea Science and Engineering Foundation, and Earthquake Engineering Society of Korea with the support of the Ministry of Construction and Transportation are the two leading institutes that execute a systematic research and collaborative program in this field. To further the activities and collaborate with international organizations, the Korea Panel on Structural Control andMonitoring were organized in cooperation with other related institutes.


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## SEISMIC ISOLATION SYSTEM

Many theoretical and experimental researches were carried out during the past decade in Korea to develop efficient base isolators and to investigate the seismic performance of various base-isolated structures, such as buildings, bridges, liquid storage tanks, storage structures for nuclear spent fuel and liquid metal nuclear reactor. The following is a summary of the researches mainly focusing on experimental works and applications of such technologies.

An experimental study was carried out on a 1/4 scale model of a 3-story building isolated with laminated rubber bearings(RB) as shown in Figure 1[Chung et al, 1999]. A series of shaking table tests and pseudo-dynamic tests were conducted on the structure under various earthquake loadings. It has been observed that the substructuring pseudo-dynamic test method using the full of large scale base-isolator is very effective for predicting the dynamic response of the proto-type base isolated structures.

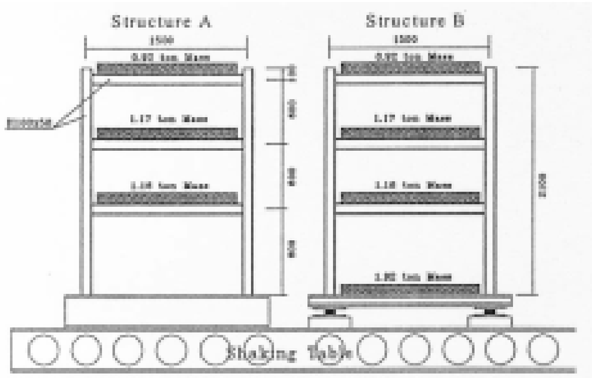


**Figure 1. Building Structures on Shaking Table**

In the test of base isolated liquid storage structure the structural model was mounted on the base isolation system consisting of four high damping rubber bearings. Scaled model tests were performed to investigate how fluid-structure interaction is affected by base isolation[Koh, Kim and Park, 1998]. Two identical models(1/16 scale) made of acrylic plates were used to compare the behavior of fixed base and base isolated liquid storage structures (Figure 2). One model was directly fixed to the shaking table, the other was mounted on the four base isolators, and both of the tests were conducted using the 6 degrees of freedom shaking table located at the Korean Institute of Machinery and Metals. By comparing the results, it is shown that the base isolation system is very effective in reducing the ground acceleration transmitted to the structure and its dynamic behavior, and the acceleration of structure and hydrodynamic pressure. While the low frequency characteristics of the base isolators can cause adverse effects on the free surface sloshing motion and on the relative isolator displacement, it is shown that careful selection of mechanical properties of isolators with a certain lower limit on the effective frequency can guarantee the dynamic responses of the storage tanks and enhancement of stability of stored objects inside liquid against earthquake excitations[Park, Koh and Kim, 1999].

**Figure 2. Shaking Table Test of Base Isolated Liquid Storage Structure**

A series of shaking table tests were conducted on a 1/5 scale bridge model supported by the base isolation system using laminated rubber bearings and hydraulic dampers under various earthquake loadings as shown in Figure 3[Yun et al, 1998]. The test results strongly show that the laminated rubber bearings cause the natural period of the bridge structure to increase considerably, which reduces significantly the deck acceleration and the shear forces on the piers. The results also demonstrate that the hydraulic dampers enhance the system's capacity in dissipating energy to reduce the relative displacement between the bridge deck and the pier.

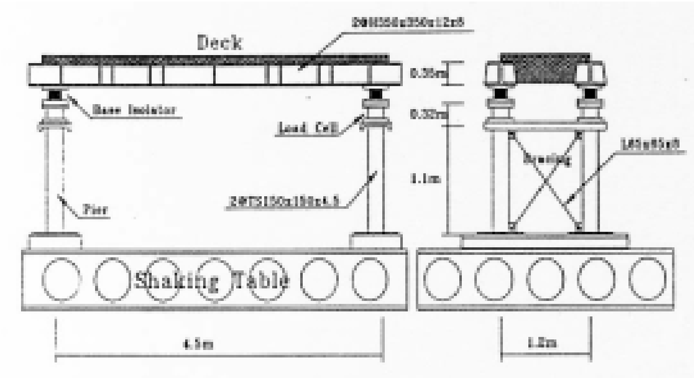


**Figure 3. Isolated Bridge Model on Shaking Table**

To improve the seismic performance of a liquid metal nuclear reactor, which is in the stage of the conceptual design, the base isolation of the reactor building structure with the lead rubber bearings(LRB) is under investigation(Figure 4)[Yoo, Lee and Koo, 1998]. The wall thickness of the reactor and the metal containment structure have to be much thinner than those of the conventional pressurized water reactor to reduce the thermal stress caused by the high operational temperature of 530 °C. Therefore, the structural instability becomes an important issue. The seismic isolation is considered to reduce the earthquake load on the reactor. Series of tests were conducted to investigate the characteristics of the lead rubber bearings with different diameters of the lead plug, particularly on the stiffness and damping. The test results indicate that the damping ratio increases as high as 30 %, as the diameter of the lead plug becomes about 30% of that of the lead rubber bearing. A preliminary design for the lead rubber bearing has been completed, and shaking table tests on a scaled model of the reactor building will carry out in the near future.

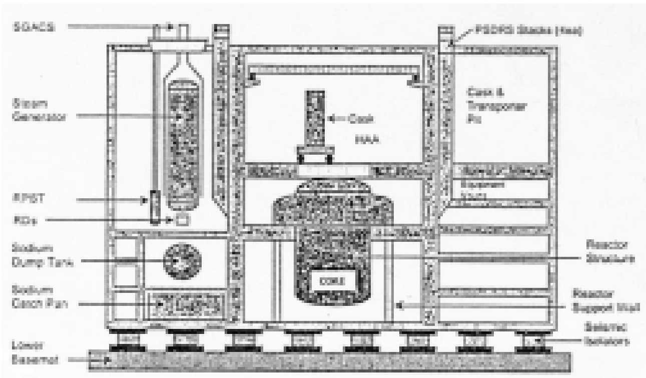


**Figure 4. Liquid Metal Nuclear Reactor**

For bridges, the use of base isolation has been recently considered and actually applied to some cases. However, there are no provisions for the use of seismic isolation in the Korean design specification for bridges. The Ministry of Construction and Transportation has launched a multi-year research project which will eventually develop a draft of provision for seismic isolation design of bridges. In this project, analytical investigations for optimal ductility demand and life cycle cost effectiveness and experimental works are being performed. Based on minimum life-cycle cost concept, an economical efficiency evaluation method for seismic-isolated bridges was developed[Koh and Song, 1999]. This method was able to consider the properties of input ground motion, limit states and failure probabilities of seismic-isolated bridges, and to investigate economical efficiency of seismic-isolated bridges under various site conditions and levels of input motion. As a result of numerical example, seismic-isolated bridges are shown to be more economical in low seismicity region and hard-rock ground condition.

Applications of the base isolation technique to the real structures began just recently in Korea although there have been some applications by using elastometric bearings. However, it is expected that the number of the applications will increase very rapidly, particularly for bridges. In 1997, there are more than 20 cases of bridge design using the base isolation, which were approved by the Korea Highway Corporation. The first cases of the base isolated building and bridge are briefly described below.

The first base-isolated building in Korea is a 3 story steel structure, which has completed in 1998. It is a laboratory building of Unison Corporation, which is a manufacturer of rubber bearings for bridges and other industrial facilities[Kim et al, 1998]. The dimension of the building plan is 28m ×12m, and the height is 13.5m. It is designed for earthquake load with the horizontal PGA of 0.12g. The design effective natural period is 1.67 sec, and the equivalent damping ratio is 0.30. Based on the preliminary design of the base isolators with lead rubber bearings and the characteristic curves, the performance of the base-isolated building was investigated numerically for various levels of the PGA. The results show that the reduction ratio of the earthquake load increases as the magnitude of the ground motion increases.

The first base-isolated bridge in Korea is an approach section of the Kwangan Grand Bridge under construction in Pusan[Kim, 1998]. It is a continuous truss section with 3 spans. The length of each span is 120m. It was designed for the earthquake load with a PGA of 0.14g. The design effective natural period is 1.82 sec. The bridge section with the base-isolators using lead rubber bearings is illustrated in Figure 5. The earthquake responses were evaluated in the longitudinal direction for various levels of the earthquake excitation.

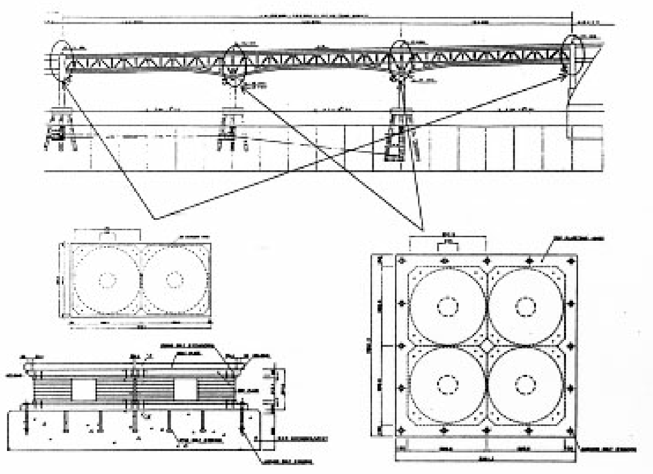

**Figure 5. Approach section of the Kwangan Grand Bridge with Lead Rubber Bearing**

## ACTIVE AND PASSIVE CONTROL SYSTEM

Active and hybrid control systems have been investigated in Korea since 1994. These systems are actively studied mainly for long-span bridges and high-rise structures subject to wind actions. Various control algorithms including LQR, direct output feedback[Koh, Park and Park, 1995] and LQG/LTR[Koh et al, 1997] were studied in the beginning. Recently, a robust and optimal controller design method using $H_\infty$ control theory was developed for the systems which have uncertain natural frequency and design constraints[Koh, Park and Park 1999]. An optimal controller design method considering stroke limitation of a Hybrid Mass Damper (HMD) system was proposed for the HMD of the air traffic control tower in Inchon International Airport under construction[Koh et al 1998]. A sliding mode fuzzy control algorithm was also studied [Yun and Kim, 1998].

Experimental study on the active control systems for large civil structures is relatively in the early stages. Shaking table tests were carried out on a single degree of freedom model equipped with active tendon or active mass damper[Koh, Park and Park, 1995]. A one-year research project for the development of an adaptable hybrid mass damper system is in progress. The HMD system is developed to have an adaptable feature that it can control structures under system variation. Experimental works for a scaled model structure is also performed. The Korea Science and Engineering Foundation have supported the project.
As an alternative to active aerodynamic control method to suppress flutter of long span bridge deck, a new passive aerodynamic control method was proposed[Kwon, Jung and Chang, 1999]. This method uses control plate that is oscillated by TMD-like mechanism. Effectiveness of the proposed model was verified through wind tunnel test, and unsteady aerodynamic forces were measured for analytic study.

An application of passive energy dissipation has been studied for the vibration control of the Korean-type high-speed railway bridge[SNU, 1998]. The vibration characteristics of the Korean-type high-speed railway bridge under the high-speed moving train loads was identified and possible use of viscous and viscoelastic dampers for the vibration control was investigated by using efficient finite element method considering nonlinear behaviors. Two and three span continuous bridges, of which span lengths are 40m and 25m, respectively, are the standard bridges of the Korean-type high-speed railway bridge. Dampers are located from center of each span. It was verified that such dampers play a role as structural damping and the transient vibration of the bridge is effectively controlled. The maximum resonance vibration is reduced, which enables the use of more compact bridge section for Korean-type high-speed railway bridge. The study on the optimal position and capacity of the damper are under investigation.

The first application of active structural control to civil engineering structure in Korea is the air-traffic control tower(Figure 6) at the Inchon International Airport under construction. The height of the tower is 100.4m. Two hybrid mass dampers(HMD) were installed in the 19th floor at the elevation of 80m to reduce the wind vibration for human comfort in the control room (Figure 7). The fundamental period of the tower is 1.44 sec, and the corresponding modal mass is 1080 ton. The total mass of two HMD's is 11 and 13 ton in two horizontal directions. The hardware of the HMD was designed by Mitsubishi Steel, Japan(Figure 7). The design wind speed for evaluating the human comfort is 29.4m/sec with a return period of 5 years. The aerodynamic characteristics of the tower were determined through the wind tunnel tests using a 1/150 scale model in Hyundai Institute of Construction Technology. Performance of the HMD was evaluated by intensive numerical simulations using time history, stochastic, and response spectrum analysis[SNU, 1997].

**Figure 6. Construction of ATC tower at IIA, Korea**

**Figure 7. Hybrid Mass Damper installed in the ATC Tower**

A tuned mass damper(TMD) was considered for control of the wind vibration of the air-traffic control tower at the Yang-Yang International Airport[Kim, 1997]. The height of the tower is 80.8m and the control room is located at the 15th floor. The TMD is to be installed at the mass center of the 13th floor. The design wind speed for estimation of human comfort is 16.8m/sec with a return period of 1 year. The fundamental period of the tower is 2.59 sec, and the corresponding modal mass is 1174 ton. Two cases of the mass ratio of the TMD are considered: 0.01 and 0.02. The optimum values of the resonant frequency and damping ratio of the TMD are determined using the equations suggested by Den Hartog. After wind force coefficients were evaluated through wind tunnel tests using a 1/120-scale model, numerical simulation analysis was carried out to investigate the effect of the TMD. The results indicate that the acceleration at the control room can be reduced to 60% of the case without TMD by using the TMD with a mass ratio of 0.01. It has been also found that the expected number of the days exceeding the vibration limit for human comfort may be reduced to less than 1 day a year.

## SYSTEM IDENTIFICATION AND MONITORING

System identification method using ARMA and ARMAX models have been investigated since the late 1980s. Recently sequential prediction error method was used to estimate ARMAX model [Lee and Yun, 1991][Yun et al, 1997]. Because of noise in measurement data and possibility of divergence during parameter estimation process for complex structures, neural network system was introduced to consider uncertainty of system properties and measurement data [Bahng and Yun, 1996]. Another approach to identify parameters of the structural system was proposed since 1995 [Shin, 1995]. In that approach, constrained nonlinear optimization method was used to estimate unknown parameters. System was parameterized using parameter group updating scheme that reduces sparseness in measurement data and also reduces unknown variables that result in improvement of convergence [Shin and Koh, 1996, 1997, 1999]. Regularization technique was applied to constrained nonlinear optimization process to alleviate the ill-posedness of the inverse problem [Yeo, 1999]. To estimate parameters of nonlinear system, a method using incremental equation error estimator based on incremental form equation of motion was proposed [Kwahk, 1999].

Actual structural monitoring systems have been applied to long span bridges such as suspension bridges and cable stayed bridges for the purpose of the verification of the construction accuracy, early detection of the unusual behavior and health monitoring[Chang, Kim and Jang, 1997]. Monitoring systems are in operation at Seohae Bridge(cable stayed bridge, main span 990m) and Youngjong Bridge(suspension bridge, main span 550m) that are under construction, and have already been used for Namhae Bridge(suspension bridge, main span 660m) and Chindo Bridge(cable stayed bridge, main span 484m) for the purpose of maintenance.

## KOREA PANEL ON STRUCTURAL CONTROL AND MONITORING

To further the activities and collaborate with international organizations, the Korea Panel on Structural Control was established in December 1998. For the moment the Korea Panel consists of more than 50 members from universities, research institutes and industries. All the members are active researchers in the field of structural engineering, earthquake engineering and wind engineering. The objective of the Panel is to advance the science and practice of structural control and monitoring in Korea by holding regular workshops and seminars, exchanging information among members, extending technical co-operation, and co-operating with the activities of International Association for Structural Control (IASC). A draft of Bylaws of the Korea Panel has been completed and is being revised as of August, 1999. The Korea Panel keeps in close contact with other organizations in Korea. Among them, the Korea Earthquake Engineering Research Center supported by the Korea Science and Engineering Foundation and Earthquake Engineering Society of Korea with the support of the Ministry of Construction and Transportation are main participating organizations. As the first international activity, the Korea Panel served as one of organizing institutes for the International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures held in Cheju, Korea in August 1999. This was a great chance to meet the members and discuss their research results with worldwide leading researchers in the field of structural control.

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