Research and Development in the U.S.-Japan Cooperative Structural Testing Research Program on Smart Structural Systems

by

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ABSTRACT

Building Research Institute conducted a 5-year research and development project of "Smart Materials and Structural Systems" in 1998 as a part of U.S.-Japan cooperative research efforts. U.S. Counterpart is National Science Foundation. Smart Structural Systems (also called as Auto-adaptive Media) are defined as systems that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life. The research and development of (1) Concept and performance evaluation method of smart structure system, (2) Sensing of structure performance, and (3) Development and evaluation of structural elements using smart materials were conducted.

KEYOWORDS: Auto-adaptive, Engineered Cemetitious Composites(ECC), Induced Strain Actuators(ISA), Magneto-Rheological(MR), Monitoring, Shape Memory Alloy(SMA), Smart, Structure, System

1. INTRODUCTION

A conventional structural system is designed to achieve a set of intended functions under pre-selected loads and forces. Such a conventional system can not successfully develop its ability against unexpected loads and forces unless a large safety factor is provided for safety limit states to take into account various uncertainties in load and force amplitudes and structural response. Furthermore, since seismic design requirements have been improved after each bitter lessons learned through past earthquake disasters, the safety level of old buildings are always inferior to new buildings as evidenced in many past earthquake disasters, e.g., the 1995 Kobe earthquake disaster. Strengthening or removal of those old buildings becomes necessary to protect societal welfare.

Smart Structural Systems are defined as structural systems with a certain-level of autonomy relying on the embedded functions of sensors, actuators and processors, that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life [1.1].

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2. TARGET ISSUES AND RESEARCH ORGANAIZATION

The research and development are conducted focusing on the following issues.

1. Concept and performance evaluation: A series of auto-adaptive and high-performance systems are developed, and methods of performance evaluation are investigated.
2. Sensing of structure performance: Damage detection methods utilizing smart materials as sensors, such as Optical Fiber, Carbon Fiber, Shape Memory Alloy (SMA), and a Piezoelectric Ceramic (PZT) in addition to existing sensors are investigated, and methods for system identification associated with damage detection are studied.
3. Development and evaluation of smart structural elements: Devices utilizing the auto-adaptive material such as SMA, PZT, Magneto-Rheological (MR) and Electro-Rheological (ER) Fluids, high tensile strength and ductility concrete, self-repairing material are developed.

To achieve the three research objectives, following three sub-committees have been formed under Technical Coordinating Committee of the project, chaired by Prof. S. Otani, University of Tokyo:

"Sub-committee on structural system" chaired by Prof. A. Wada of Tokyo Institute of Technology,

"Sub-committee on sensing and monitoring technology" chaired by Prof. Y. Kitagawa of Hiroshima University,

"Sub-committee on effector technology" chaired by Prof. T. Fujita of Institute of Industrial Science, University of Tokyo.

The research organization is illustrated in Figure 1. The Building Contractors Society, the Housing and Urban Development Cooperation, the Building Center of Japan, and several materials and sensors makers participate in this R/D project.

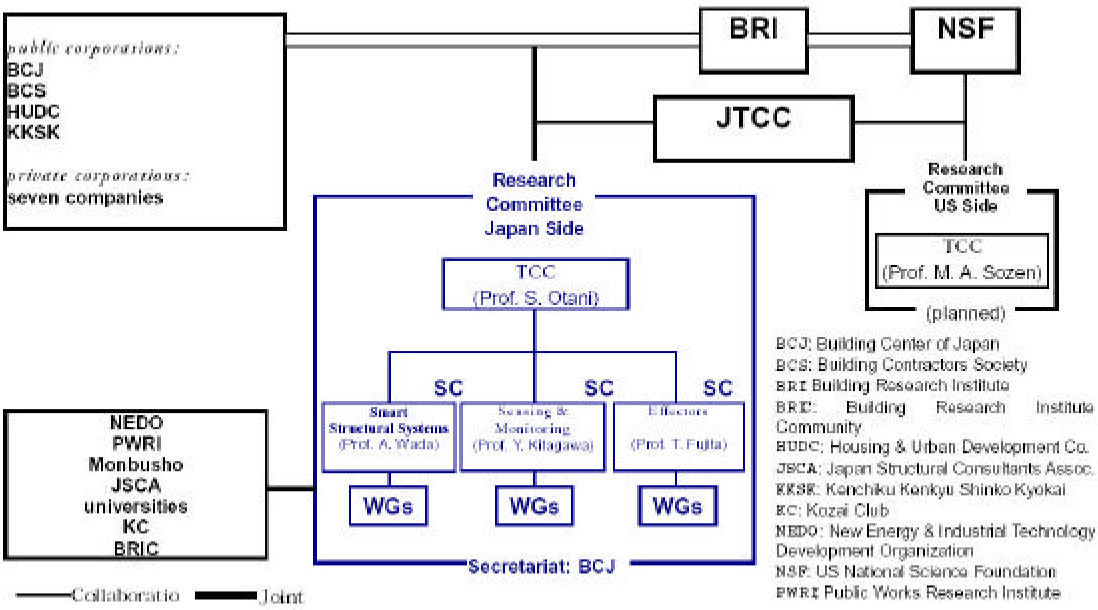


Fig.1 The Research Organization on Smart Structure

Table1 Research Time Table

	1998	**1999**	**2000**	**2001**	**2002**
System	Concept of Structure				
		Proposal of SSS		Large Scale Test	
				SSS Evaluation GLs	
Sensor	Survey of Sensors		R/D of Smart Sensors		
	Survey and R/D of Monitoring			Large Scale Test	
				Sensor & Monitoring GLs	
Effectors	Survey of Smart Materials				
		Application to Buildings		Large Scale Test	
				Smart Materials GLs	

This research program started at 1998 for 5 years. The research and development of (1) Concept and performance evaluation method of smart structure system, (2) Sensing of structure performance, and (3) Development and evaluation of structural elements using smart materials were conducted according to the timetable tabulated in Table-1. And these accomplishments were summarized to smart structure system evaluation guidelines, sensor and monitoring guidelines, and application guidelines of smart materials, through the large-scale test for performance verification.

In this research periods, US-Japan Joint Technical Coordinating Committee (JTCC) were held at Tsukuba[2.1] and Hawaii[2.2] in 2000, and at Tsukuba[2.3] in 2002. Last JTCC was accompanied with workshop on smart structural system [2.3]

3. SMART STRUCTURAL SYSTEMS

3.1. Outline

The performance level required of building structures becomes higher and wider in these days. It is considered that the smart structural systems are one of solutions to realize such performance of building structures. The concept of smart structural systems was initially proposed in the field of aerospace engineering. In this research and development project, we try to apply the concept of smart structural systems to building structures. Based on this concept, some smart structural systems are developed. Their performance is examined by numerical analyses and/or dynamic tests. Finally, the performance evaluation guideline for smart structural systems is proposed.

3.2. Concept of Smart Structures for Buildings

The concept of smart structural systems was initially proposed in the field of aerospace engineering, where the smart structural system was defined as “a system that can detect damage, restrain damage propagation, control the response from external disturbance actively, and adapt its configuration to optimum state for the environment.” The objectives and needs of a smart structural system for buildings are different from those of aerospace engineering as shown in Table 3.1. Thus we need to revise the concept of smart structural systems when applying it to buildings. In this project, the smart structural system for building structures is defined as “a structural system with a certain level of autonomy relying on the embedded functions of sensors, actuators and/or processors, that can automatically adjust structural characteristics, in response to the change in external disturbances and environment, toward structural safety and serviceability as well as the elongation of structural service life” [3.1]. Based on this concept, we develop three types of smart structural systems, which are auto-adaptive structural systems, reinforced concrete (RC) structural systems with damage fuses and innovative life safety systems. The research organization for these systems is shown in Fig.3.1.

3.3 Development of Smart Structural Systems

3.3.1 Auto-adaptive Structural System

Auto-adaptive structural systems have auto-adaptive features using smart materials and/or smart methods. These systems are expected to possess higher performances relying on the embedded functions of sensors, actuators or processors than the conventional structural systems. Two examples of these systems are shown in Fig.3.2. One is a hybrid system with semi-active vibration control dampers made with smart material for super-structure and base isolation. This system can reduce seismic response acceleration as well as displacement. The other is a rocking structural system with yielding base plates. This system has yielding base plates at the bottom of each steel column at the first story. When the base plates yield during a strong earthquake, the building causes rocking vibration automatically to reduce its seismic response. Although the rocking system has neither specific smart materials nor computer control systems, it satisfies the concept of smart structural systems. Two series of shaking table tests were carried out to examine the seismic response of the rocking structural system with yielding base plates. Two types of test frames are shown in Photo.3.1. Two types of base plates are also shown in Photo.3.2. From the results, it has been concluded that the base plate yielding systems reduce effectively the seismic response of building structures [3.2][3.3][3.4].

3.3.2 RC Structural Systems with Damage Fuses

The example of RC structural systems with damage fuses is shown in Fig.3.3 and photo.3.3. To realize this system, the damping effect of damage fuses such as dampers was studied. The seismic performance evaluation method considering the damping effect has been developed. This evaluation method is based on the capacity spectrum method [3.5], the energy input rate spectrum method and so on.

3.3.3 Innovative Life Safety Systems

Simple and effective methods to reinforce low-rise inferior structures were studied. First of all, we conducted a questionnaire survey to academics, graduate students and structural engineers. They have presented us with new plans of smart elements and/or systems for reinforcement or life safety. The ideas collected were summarized into the following methods; 1) uplift of structures, 2) support for structures, 3) isolation systems, 4) adaptive structures, and 5) connecting systems. With considering the survey results, we proposed new innovative life safety systems easy to set up, which use loose linking elements. The concept of the system is illustrated in Fig.3.4. The seismic response of this system was examined by numerical analyses and shaking table tests. Test specimen is shown in Photo.3.4 and Fig.3.5. From the results, the relation between the setup of the systems and its reinforcement effects has been cleared [3.6].

3.4. Performance Evaluation Guide Line

The contents of performance evaluation guideline for smart structural systems are as follows;

Chapter 1 Introduction
Chapter 2 Target performance
Chapter 3 Performance evaluation against seismic motions and wind forces
Chapter 4 Maintenance
Chapter 5 Safety
Chapter 6 Reparability
Chapter 7 Health monitoring after construction

According to this guideline, structural engineers are required to explain the target performance of a building to its owner or user using performance matrices. And the performance of the building must be generally evaluated by the time history analysis. The reparability of the building is examined by analyzing the life cycle cost of it. The performance evaluation guideline will be published this year.

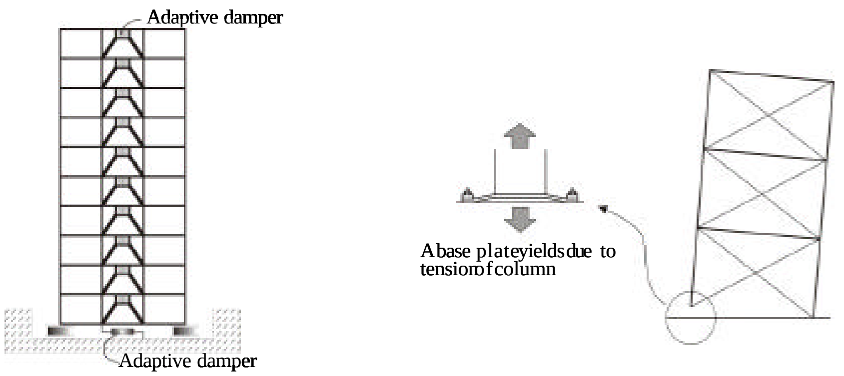
3.5. Conclusions

1) The concept of smart structural systems for building engineering was proposed.
2) Based on the concept of smart structural systems, new structural systems were proposed and developed.
3) The performance of proposed smart structural systems was examined. Especially, superior performances of rocking structural systems with yielding base plates and retrofit systems using loose linking elements were shown successfully by shaking table tests.
4) The performance evaluation guideline was proposed.

SMART STRUCTURAL SYSTEM
Sub-committee
(WADA, A., Tokyo Inst. of Tech.)

- WG1 (Auto-adaptive structural systems)
  (WADA, A., Tokyo Inst. of Tech.)
- WG2 (RC structural systems with damage fuse)
  (KABEYASAWA, T., Tokyo Univ.)
- WG3 (Innovative life safety systems)
  (NAKASHIMA, M., Kyoto Univ.)

Fig.3.1 Research organization for smart structural systems



(a) Hybrid system with semi-active vibration control

(b) Rocking structural system with yielding base plates

Fig.3.2 Two examples of auto-adaptive structural

(a) Five-story test frame

(b) Three-story test frame

Photo.3.1 Two types of test frames for shaking table tests

(a) Base plate with two wings for five-story test frame

(b) Base plate with four wings for three-story test frame

Photo.3.2 Two types of base plates

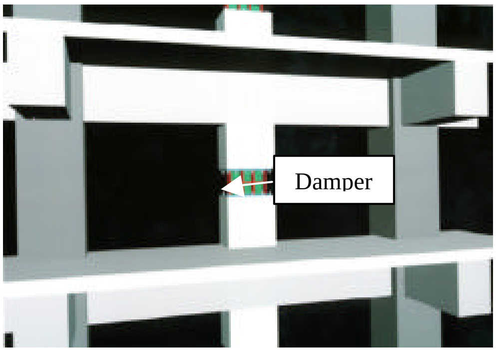


Fig.3.3 RC frame with damage fuses (dampers)

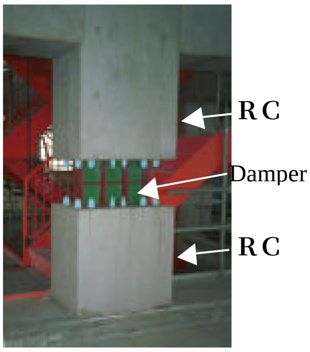


Photo.3.3 Example of dampers

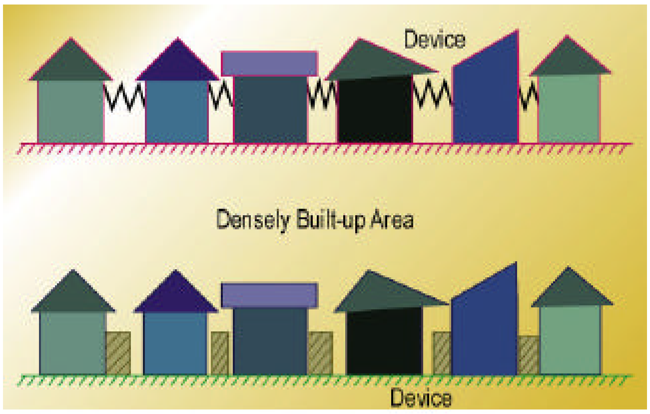


Fig.3.4 Retrofit system using loose linking elements

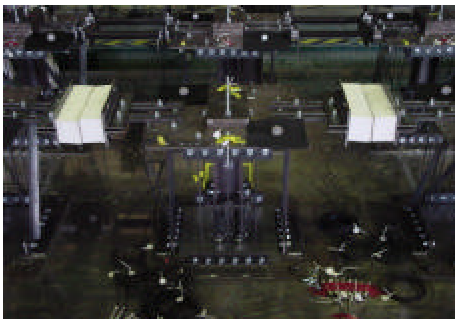


Photo.3.4 Test specimen for the retrofit system using loose linking elements

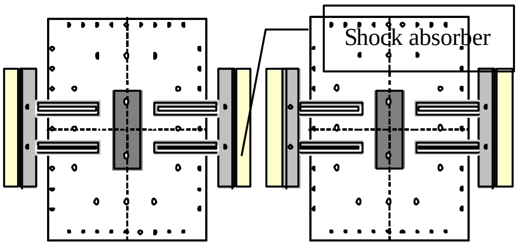


Fig.3.5 Plan of test specimen

4. SENSING AND MONITORING TECHNOLOGY

4.1 Outline of Sensing and Monitoring Technology

Objectives of sub-committee of "Sensing and Monitoring Technologies" are

1) To research and develop on systems that are provided with sensors and processor or with sensors with its own processor

2) To research and develop on smart sensors

Actual targets of research and development as shown below are defined after having discussed among members of sub-committee and working groups have been organized in accordance with these targets. Research organization is shown as Fig.4.1

Procedures of health monitoring are shown as Fig. 4.2. Inside of dash line in Fig 4.2, we tried something in this project. That is, from measuring data, we can evaluate physical parameters. But how to evaluate structural

Sub-Committee of Sensing and Monitoring Technologies (Y. Kitagawa, Keio University)
- structural health monitoring WG (S. Nakai, Chiba University)
- smart sensors WG (A. Mita, Keio University)
- sensor network system WG (K. Yoshida, Keio University)

Fig.4.1 Organization of Sub-Committee of Sensing and Monitoring Technologies

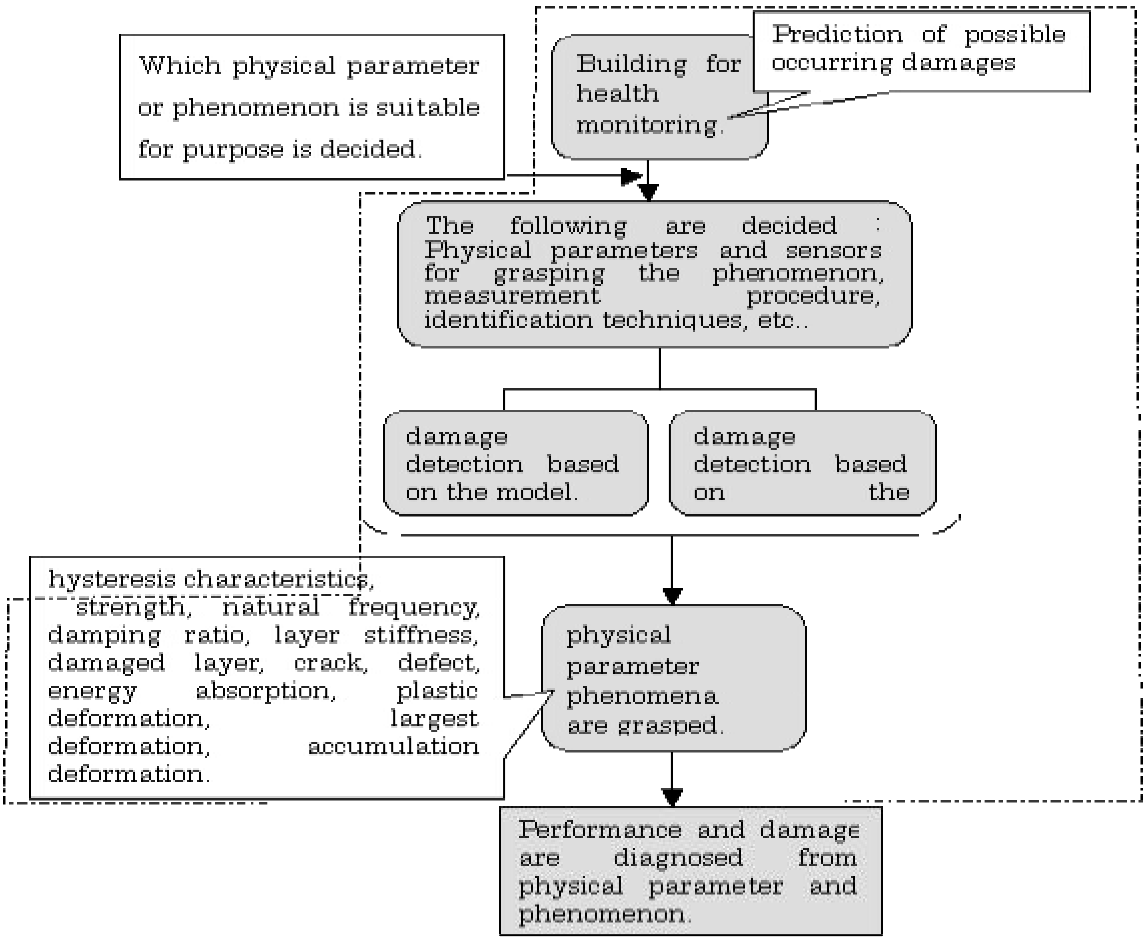


Fig. 4.2 Procedure of health monitoring

performance is not discussed in this guideline.

4.2 Structural Health Monitoring Technologies

4.2.1 Damage Detection Tests of Five-story Steel Frame

Damage detection tests of five-story steel frame with simulated damages are carried out. Test frame is five-story steel structure shown as Fig. 4.3. Fiber brag grating (FBG) sensors, accelerometers, strain gauges and laser displacement meters are installed in this test frame. We assume damages by removing studs from only one story, loosening bolts of beams, cutting part of beams and extracting braces from only one story. We apply flexibility method which is one of a damage identification methods using modal properties. We apply this method to experiments. In some cases we can estimate which story is damaged, and in other cases we cannot. If 1st story studs are removed, 1st story damage indicator is large as Fig.4.4. We also applied a method using multiple natural frequency shifts. Making use of the change in five natural frequencies due to damage, the location of damaged stories can be pinpointed. In both methods, we cannot identify damaged story in some cases. Some methods other than methods using modal properties have to be tried to apply in such cases.

Fig. 4.3 Exterior of Test Frame

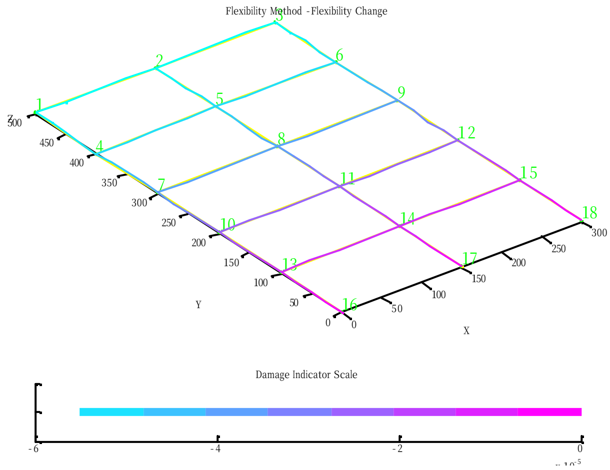


Fig. 4.4: Flexibility changes for no studs at 1st story

4.2.2 Damage Detection Test Using Large Scale Test Frame

Shaking table test using a three-story large-scale steel structure with cementitious devices are carried out. The test frame is a three-story steel structure shown as Fig. 4.5. The test frame floor height is 1.8m, total height is 5.4m, floor plan is 4mx3m and there are two spans in excitation orthogonal direction. Shaking table test is carried out at large-scale earthquake simulator facility of the National Research Institute for Earth Science and Disaster Prevention. Cementitious devices

Fig. 4.5 exterior of test

are installed in the center frame of tested structure and devices are actually damaged during the shaking. We carry out damage detection test by damaging devices and we measure the process of damaging devices. We apply damage identification methods to these phenomena. Two types of identification are tried. One is a) identification using the data under excitation and the other is b) identification using the data of before and after of the excitation. In both cases, we use identification method by ARX model. From identified results, natural frequency decreases, damping ratio increases and story stiffness decreases as experienced amplitude increases or input amplitude increases. Story stiffness results are shown as Fig. 4.6. Almost all characteristics by microtremor can be estimated to be same as those by white noise. A model using stick-slip elements is proposed. Natural frequency, damping ratio and story stiffness described by this model are consistent with experimental results.

4.3 Smart Sensor Technologies

4.3.1 Objective and Targets

The objective of this working group (WG) is to research and develop on smart sensors that measure and identify the state and phenomena of building structures and members. And finally This WG will propose guidelines for application of smart sensors for the health monitoring of building structures.

4.3.2 Sensors

This WG has surveyed materials, equipment, and systems that have possibility to use as sensors, and has studied on utilization and application of the sensors that have higher feasibility for the smart sensor. Following sensors were discussed.

1) Optical fiber sensors for displacement. deformation, strain, heat, and water
2) Carbon Fiber sensor in concrete for crack, strain, and deterioration of concrete
3) Radio-Frequency Identification (RFID) Tag sensor for crack on concrete

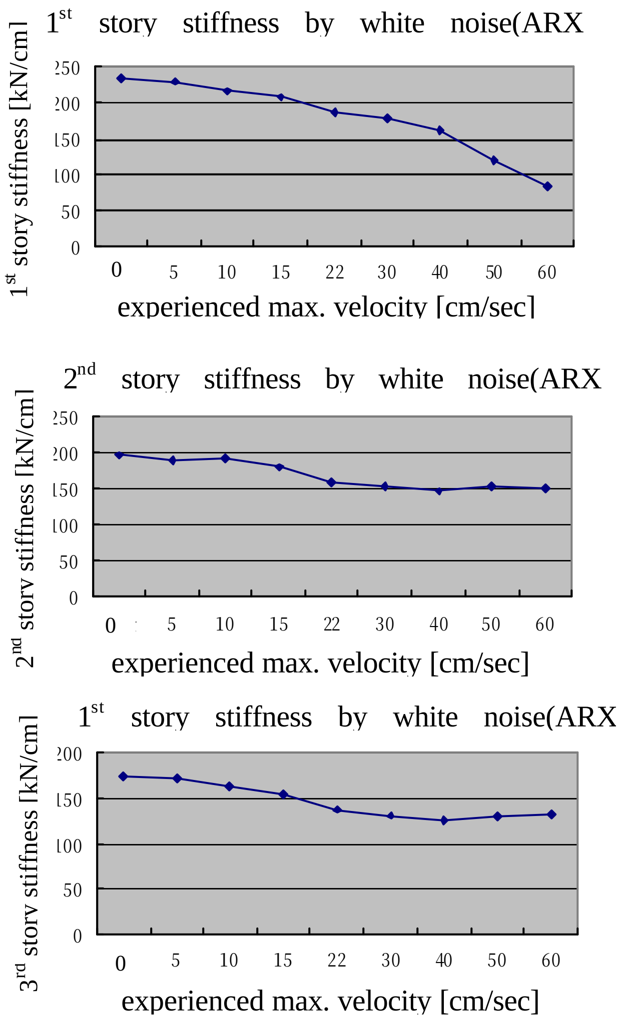


Fig. 4.6 : Stiffness change according to experienced max. velocity

4) Wave sensors for deterioration of concrete
5) Temperature sensor for plastic deformation of steel
6) Maximum value memory sensor for displacement
7) Two-wire sensing system with processor-built-in sensors

4.3.3 Radio-Frequency Identification (RFID)Tag sensor

The original concept of this sensor was proposed by Prof. Wood. This sensor consists of a IC tip with a tag number and an antenna which wire is elongated by additional wire, tape and carbon wire, as shown in Photo 4.1 and Fig.4.7. When a big crack occurs in the structural member, the aluminum tape will be broken and the RF Transmit and Receiver cannot detect the RFID Tag sensor.

Only one RFID Tag sensor detected the crack occurred at the bottom of the RC member and the other sensors could not detected cracks, because almost cracks are less then 0.04 mm in width and the aluminum tapes have large ductility for crack detection. Therefore other wire materials such as small copper wires and carbon strings should be checked for detection of cracks.

4.3.4 Two-wire Sensing System with Processor-built-in Sensors

Outline of composition of the two-wire sensing system for the three-story steel frame test is shown in Fig.4.8. The system consists of 1) Processor-built-in sensors, 2) Two wires, 3)

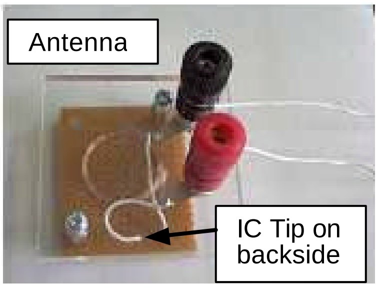


Photo 4.1 RFID Tag

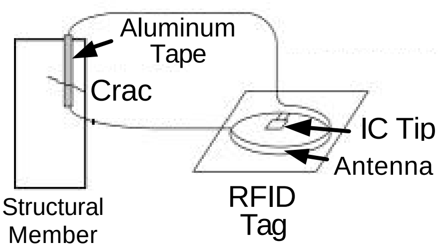


Fig.4.7 Schematic view of application of RFID Tag sensor to the structural members

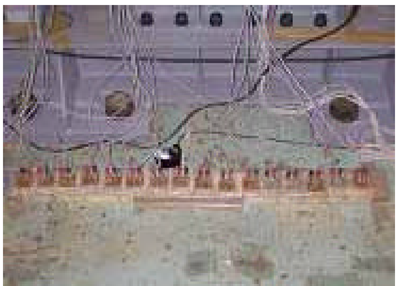


Photo 4.2 RFID Tag sensors

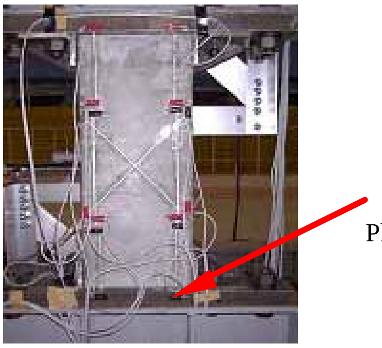


Photo.4.3 Aluminum tape for RFID

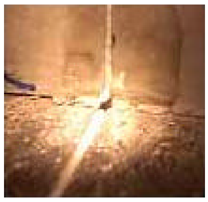


Photo4.4 Broken aluminum tape at the bottom of the RC member

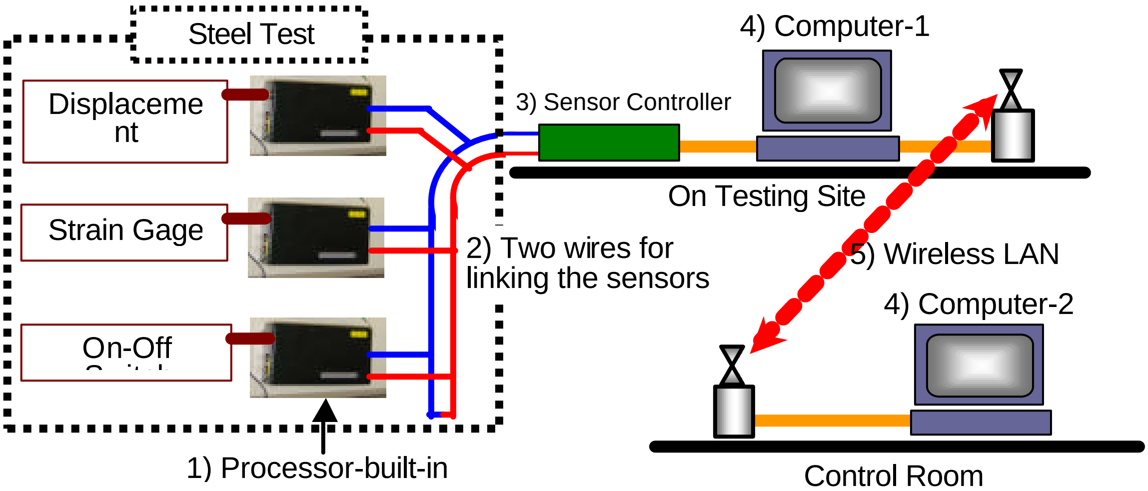


Fig.4.8 Outline of composition of wire -saving sensor system for the three-story steel frame test

Sensor controller, 4) Two computers, and 5) Wireless LAN system.

The processor-built-in sensor has a IC tip for strain measuring and a IC tip for A/D conversion and communication. Specifications of the processor-built-in sensors are as follows.

1) 1 channel for voltage and strain input for displacement transducers and strain gages

2) 4 channels for on-off switch for crack detection

3) 8 bits accuracy of A/D conversion

4) 10 msec interval of A/D conversion

5) 64 words for memory

6) Memory for maximum and minimum values

7) Memory for the local peak values (Fig.4.9)

8) Two-wire link for electric power supply and communication with controller

Fig.4.10 shows the comparison between peak values obtained from the wiring-saving sensor system and those from simulation using the measured data by dynamic measuring system. The peak values are in good correspondence. But this sensor has no time information now, so we cannot gat the time history but we can get

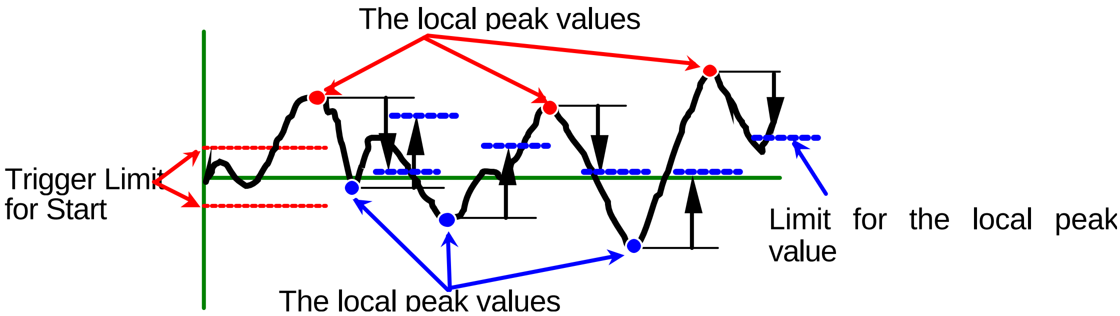


Fig.4.9 The local maximum and the local minimum values

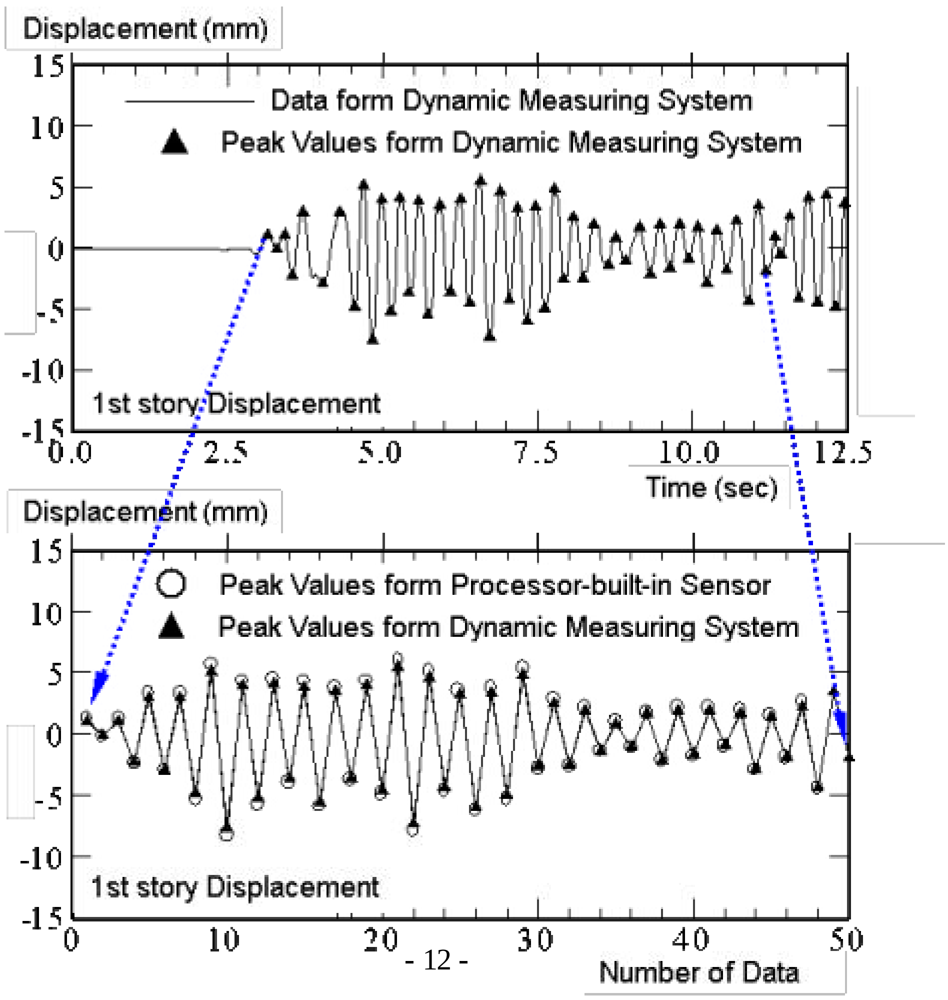


Fig.4.10 Comparison of peak date obtained from the dynamic measuring system and the wiring-saving sensor system

maximum and minimum values, each peak values and the accumulated value of data history.

4.4 Sensor Network System with RT-Linux

4.4.1 Introduction

As for the health monitoring which monitors the seismic performance of structure, it is needed to collect the data from various sensors installed in structure members and analyze them. And the collecting data system is needed.

This paper describes the "Sensor Network" which connects the installed sensors and provides health monitoring system of structures. The reference [1] showed the fundamental required items for this "Sensor Network" and this paper shows a health monitoring method of specimen which uses the "Sensor Network".

The main items are as follows (Fig.4.11);

(1) Networked Sensor System
(2) Simultaneous Measurement
(3) Real-Time Communication Mechanism
(4) Utilization of Existing Infrastructure :Local Area Network
(5) Necessity of Real-Time Identification and Diagnosis

4.4.2 Sensor Network

In these years, after the information technology made much progress, buildings are prepared by Local Area Network (LAN) and connected each others. The Sensor Network in this paper is a measurement system of sensors installed at a part of this LAN of these buildings.

The most important point in the Sensor Network is to have a real time accuracy between the measuring of sensors. The real time accuracy means the limited time between the start time of a measuring and the end time of it. The Sensor Network is needed to guarantee the same start time of a measuring in all sensors and the same sampling time. That is why the Sensor Network uses the RT-Linux which is an operating system (OS) with the function of the real time process. Fig.4.12 shows the structure of RT-Linux. RT-Linux has an added function to deal with the real time process in the high level priority among the kernel executed in OS.

The communication system of this Sensor Network uses the RT-Messenger[2] which is the new real time application that can work under the RT-Linux.

In order to decrease the process for communication as less as possible and to escape from the accidental late process by buffering, RT-Messenger is installed in the data-link-layer without TCP/IP (Transmission Control Protocol / Internet Protocol). RT-Message is defined as a packet type of RT-Messenger for receiving data of RT-Messenger from the data link layer.

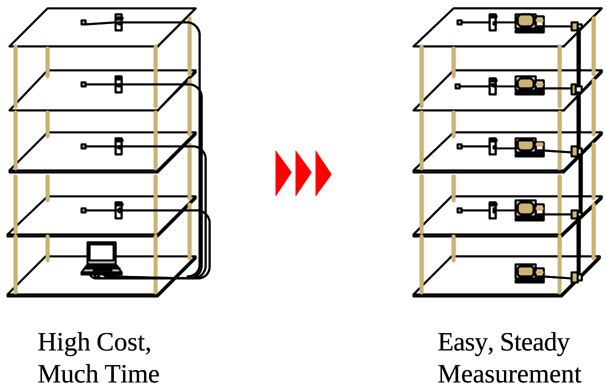


Fig.4.11 Utilization of LAN instead of Wiring

4.4.3 Preliminary Experiment

The system of Sensor Network is shown in

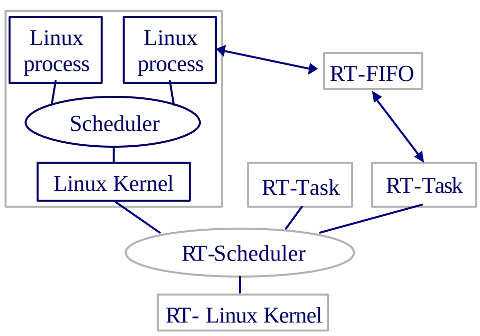


Fig.4.12 Structure of RT-Linux

Fig.4.13. RT-Messenger is installed in the 3 personal computers. The Network is 1 PC as a server, and 2 PCs as slaves for receivers. The PC properties are CPU: Pentium II 300, 400 [MHz], Kernel version of Linux: 2.2.14, RT-Linux version: 2.2.

In order to test the real time accuracy of the Sensor Network, RT-Messages are served in the time interval of 1 milli-second from the server and the late times of serving in the server and the late time of receiving in the Client-A and Client-B are measured. As a result, the late time of serve is 1.3 micro seconds in the maximum, and the late time of receive is 10.1 micro second in the maximum. After the transmit command in the interval of 1 milli-second, the time interval of serve and receive is exactly measured in 1 milli-second. It means that the late time of serve and receive is enough short to the time interval. That is why this Sensor Network has the enough real time accuracy.

And in order to verify the effects of RT-Messenger, the comparison between the system with RT-Messenger and the system without it are made. The comparison method is that 1 PC serves a packet in the time interval of 1 milli-second from RT-Task and the other PC receives the packet on RT-Task. Fig.4.14 shows the measuring results of the system with RT-Messenger.

In the system without RT-Messenger, an the side of serve, the ratio which the time interval is 1 milli-second is about 10%, and the tolerance is large. At the side of receive, the ratio which the time interval is 1 milli-second is lower than 5%, and the tolerance is large.

That is because the process interval times by the scheduler installed in Linux are guaranteed at most 10 milli-second. The RT-Linux is installed by the communication application called as RT-FIFO, but it works for the communications between the RT-Task and the user process of Linux in 1 computer, and RT-Linux does not permit to communicate RT-Task between the 2 computers directly. On the other hand, RT-Messenger permits to communicate RT-Task between 2 computers directly.

Finally, RT-Messenger is necessary for the “Sensor Network” which requires the real time accuracy.

4.4.4 Experiments

This Sensor Network is applied to the shaking test and the large-scale test.

In the shaking test, the comparison was made about natural frequencies in modes between this Sensor Network and FFT analyzer.

In the large-scale test, the comparison was made about the time history of data between this Sensor Network with the resolution of 12 bit and the high technology measurement device with the resolution of 24 bit.

According to these applications to tests, the

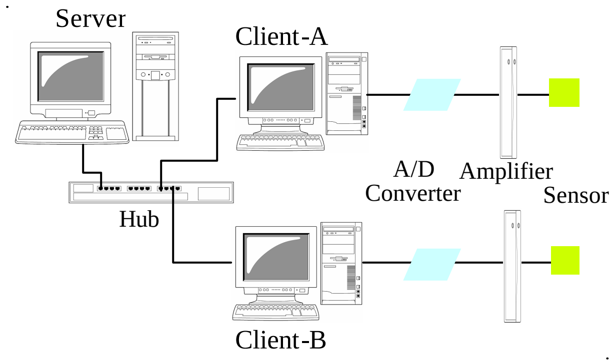


Fig.4.13 System of Sensor Network

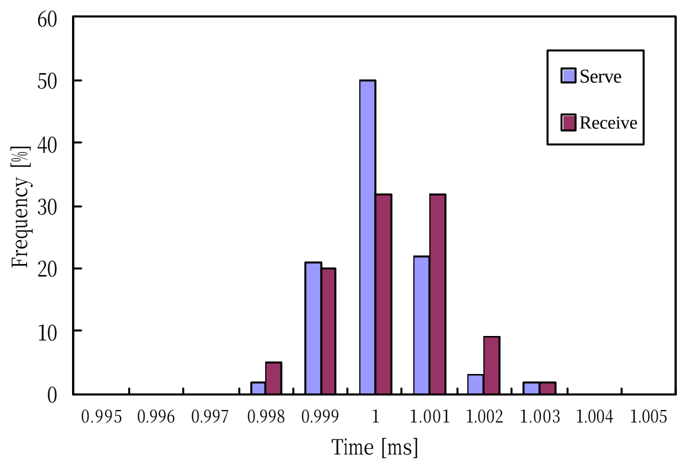


Fig.4.14 Time intervals with RT-Messenger

proposed Sensor Network has enough real time accuracy.

5. EFFECTOR TECHNOLOGY

5.1 Outline of Effector Technology

5.1.1 Research items

Purposes of researches in the “effector technology sub-committee” is to investigate characteristics of several “smart materials” and the applicability of “smart materials” or “smart members” to building structures. Due to requests to be made lighter materials and to be more effective and more reliable for control techniques, the smart materials are applied to systems in aerospace fields. On the other hands, the application of the smart materials to building use has not been popular because of necessity for a large amount of capacity and cost.

In the effector technologies sub-committee of the project “Development of Smart Structural Systems”, the smart materials, which will be applicable to the building structures in the very near future, were selected, and their characteristics and their applicability will be discussed.

The word “Effector” is defined materials and/or systems whose characteristics will be adaptive, that is, changing through external situation or external signals. These materials and systems will exert forces to structures more effectively than materials and systems will do in the passive situation. In addition, the materials are included which will make the structural performance higher during earthquake. Following items are being conducted.

i)Material characteristics and applications of the materials through summarizing results in published references.

ii)Material characteristics will be clarified through fundamental tests.

iii)Devices and systems will be produced and tested for verification as smart materials.

As materials which will be applicable in near future, following materials are selected.

a)Shape memory alloys

b)Electrorheological and magnetorheological fluids

c)Induced strain materials

d)High performance fiber reinforced cementitious composites

Research results are summarized in guidelines for characteristics of materials and devices, and applicable examples for buildings.

5.1.2 Research organization

Under the effector technology sub-committee, the research is being conducted in working groups for each materials as shown in Fig.5.1

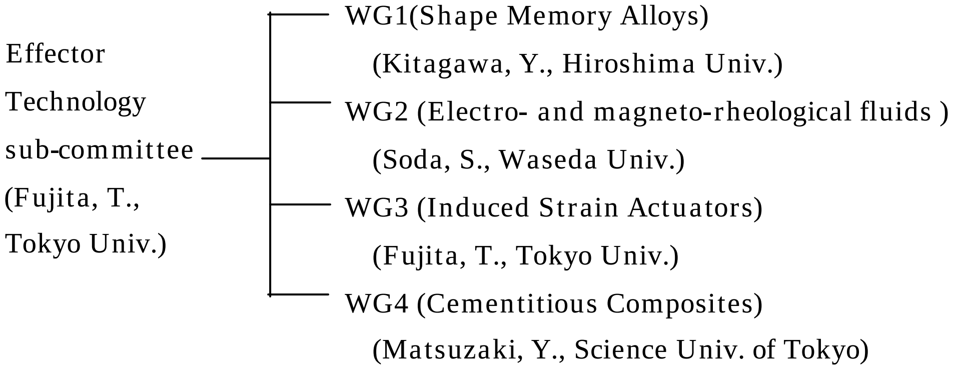


Fig.5.1 Organization of Effector Technology Sub-committee

5.2 Shape Memory Alloy

5.2.1 Research Objectives

The shape memory alloys(SMAs) shows two properties, that is, superelasticity and shape memory. These characteristics are dependent on a temperature in which the SMAs are used, as shown in Fig.5.2

This project focused on the superelastic properties of titanium-nickel alloy, currently the easiest shape memory alloy to obtain, to study its material properties as well as ways of using these material properties in building structures. In products, the alloy demonstrates stable material properties; in wire form, approximately 110 kNs of titanium-nickel alloy is used each year to manufacture antennas for mobile phones, and it is also used to make eyeglass frames. In building construction, the material has been used in the form of tensile braces for seismic reinforcement of a historical building. All of these applications have used the superelastic properties of the alloy. In wire form, the material is not only stable but has already demonstrated comparatively high performance in terms of energy absorption from cyclic loading. In this project, wires and bars were studied to determine the material properties of the alloy, with the aim of using it in building structures. And it was examined to determine the potential of their superelastic properties to control structural response of buildings.

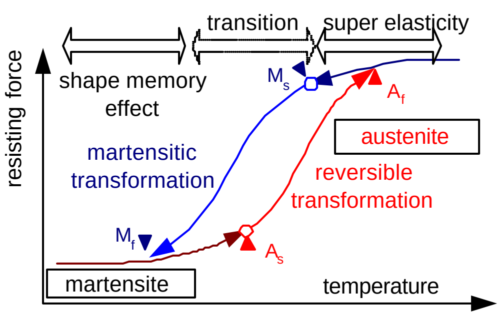


Fig.5.2 Material Phase-Property-Temperature Relation of SMA

5.2.2 Research Results

The following results were obtained, in particular from the material tests of bar prototypes(see, Figs.5.3 to 5.5).

1) In tensile tests, the material demonstrated clear superelasticity, with deformation of around 5% or less.

2) When the amount of energy absorption from cyclic loading is compared using the equivalent damping factor, the value for bars was lower than that for wires.

3) In compression tests, the material did not demonstrate perfect superelasticity; residual deformation was produced after unloading.

4) The stress-strain properties were different for tension and compression.

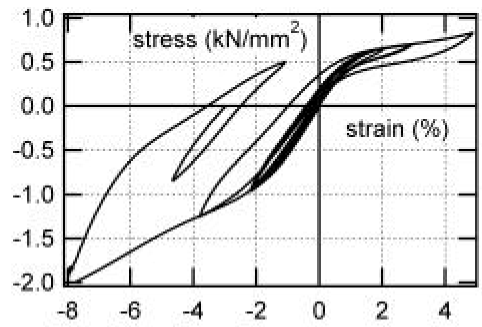


Fig.5.3 Stress-strain Relation of SMA-bar

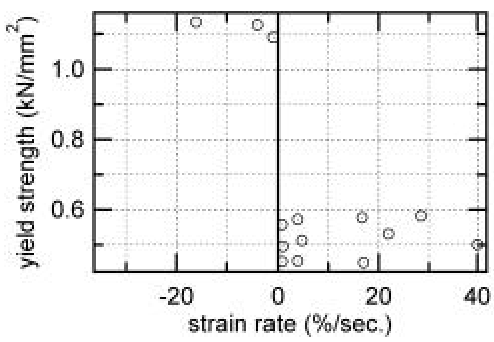


Fig.5.4 Yield Strength vs. Strain Rate

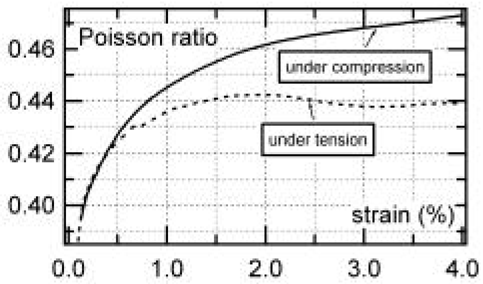
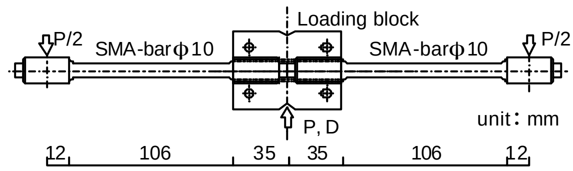


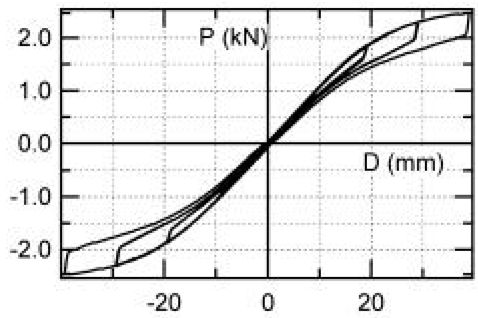
Fig.5.5 Poisson Ratio of SMA

Bars of the alloy were used to form tensile braces, bending members(see Fig.5.6), anchor bolts for column bases, and bolts for beam-column joints. Wires were used as longitudinal reinforcements for concrete members(see Fig.5.7) and tendons for prestressing members. These test specimens were studied to determine the potential of their superelastic properties to restore structural deformation to its original state (in other words, to determine their repair or restoration performance). The results of these tests show that the members demonstrated repair performance matching their material properties, and if the materials are used in a manner appropriate for the type, scale etc. of the structure, they have the potential to demonstrate both restoration performance and energy absorption. However, it was also learned that, even with the same alloy composition and method of manufacture, bars had a lower degree of energy absorption from cyclic loading under superelastic conditions. It was also learned that, in some cases, bars fractured brittlely under cyclic loading.

If one assumes that shape memory alloys will be used for response control of building structures, a member with large restoring force capacity will be needed. Accordingly, for the verification tests in this project, bars were considered to be one of the possible solutions, and so bars were used for tension members and bending members. Even with a bar form that has a large cross-sectional area, improvement of the manufacturing process is desirable to enable great energy absorption from cyclic loading to be obtained and to ensure that the material will not fracture in the early stages. In addition, the application of these bars must be designed to ensure suitable control over the range of the applied stress and deflection.

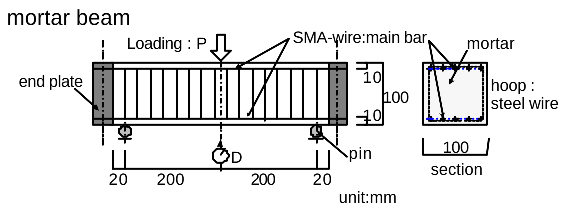


a) Test Specimen

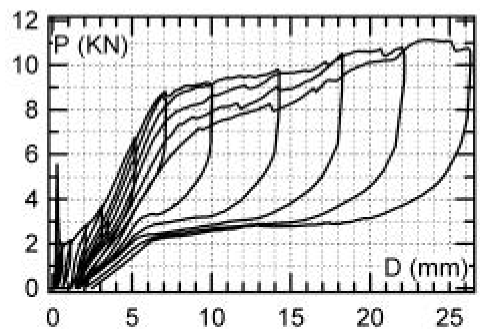


b) Force-displacement Relation

Fig. 5.6 Bending Test on SMA-bar



a) Test Specimen



b) Force-displacement Relation

Fig. 5.7 Bending Test on Mortar Beam

5.2.3 Conclusions

In this project, research focused on the superelasticity of shape memory alloys to determine their material properties and behavior when used for vibration control, etc. in building structures, and the potential for the use of these materials in building construction was discussed. Although shape memory alloys are a single material, they have two different material properties, as shown by the fact that they have not only superelasticity but a temperature domain with a shape memory effect. These two properties make shape memory alloys "smart" materials that can provide multiple functions, and thus they are both attractive and intriguing as metal materials.

It is thought that limited objectives for application, careful scrutiny of the performance needed to achieve these objectives, and effective use of the properties of these materials will enable optimal design for building structures. These materials are expected to find use in structures of various types.

5.3 Magnetorheological Fluid

5.3.1 Research Objectives

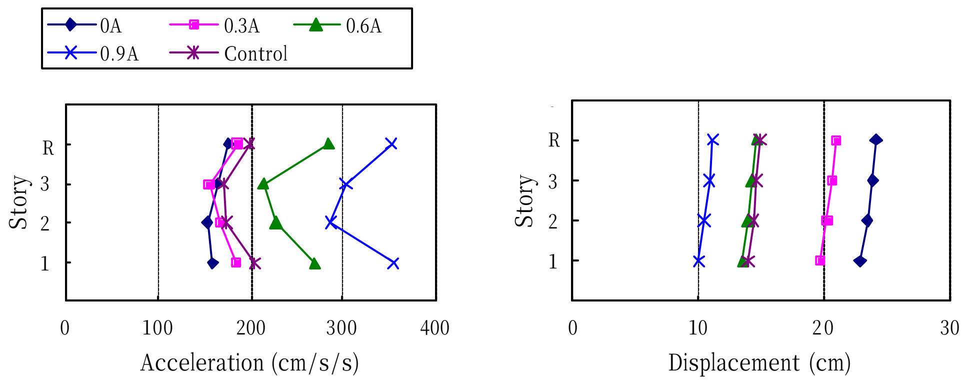
Magneto-rheological (MR) fluids have essential characteristics that change from free-flowing, linear viscous fluid, to a semisolid with a controllable yield strength when exposed to a magnetic field. This fluid is effective material for development of controllable devices. It is intended to develop a structure that changes its damping characteristic to behave adaptively against earthquake or wind forces and achieve safety and function by using MR devices with less Energy.

Some researches on application technology of MR fluid by Spencer et al. were conducted at the beginning of this project. They developed a 200kN MR damper[5.1] and proposed structural control strategies in case of base-isolated[5.2] and fixed base[5.3] building structures.

5.3.2 Researches and Development of MR Fluids and MR Dampers

Magnetorheological (MR) fluid is a dispersion of fine magnetizable particles in a liquid medium. In order to improve the stability, BRI and research group developed MR fluid *"#230"* with enhanced stability[5.4].

BRI and research group developed some MR dampers. At first, a simple MR damper (Photo 5.1) was developed in order to verify the performance of MR damper, for example, force-displacement relationship, force-velocity relationship, influence of temperature and



(a) Absolute acceleration (b) Relative displacement

Fig. 5.8 Average Values of Response of Each Story of Positive Side and Negative Side (El Centro 1940 NS, Maximum velocity is 50cm/sec) response speed of MR damper[5.5]. Then a 200kN MR damper was developed in order to verify the same items in case that the electromagnet is attached at the bypass flow portion, which is connected to the cylinder[5.6].

Photo 5.1 20kN MR Damper

Next, a long stroke MR damper (Photo 5.2: +/-295mm)) was developed for base-isolated structural model. The MR damper was used for a large scale shaking table test.

5.3.3 Verification by Large-scale Test

Semi-active control reduces both response displacements and accelerations. MR damper generates damping force, which does not depend on the piston speed so much. The target of this subject is to improve the safety and functionality and habitability by controlling the response displacements and accelerations by using MR dampers. For this purpose, a series of shaking table tests was conducted[5.7].

Figure 5.8 shows one of the test results. The controlled accelerations are reduced the same as one of 0.3A, and the controlled displacements are reduced the same as 0.6 A. This shows that semi-active control by the MR damper can reduce the response displacements while reducing the response acceleration[5.8].

5.3.4 Application to An Actual Base-isolated Building

A 400kN MR damper for an actual base-isolated building was developed and its dynamic

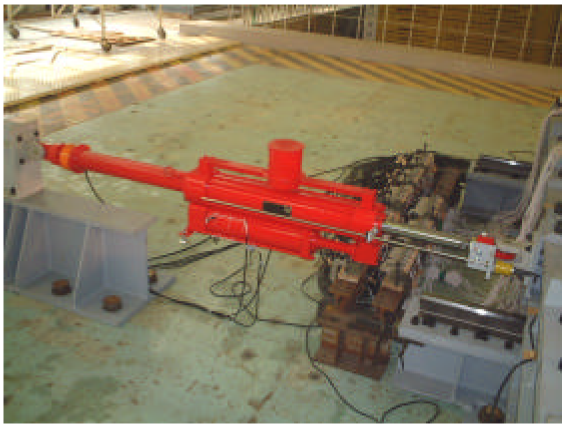


Photo 5.2 Long Stroke MR Damper

characteristics verified by experimental tests. The MR damper has 950mm (+/-475mm) stroke and by-pass flow potion. To verify the dynamic characteristics of the MR damper, a series of experimental tests were conducted by using dynamic actuator. Figure 5.9 shows the force-displacement relationship. The yield force of the MR damper increases with the rise of the electric current, and it was verified that the maximum damping force was controllable by adjusting the magnetic field[5.4].

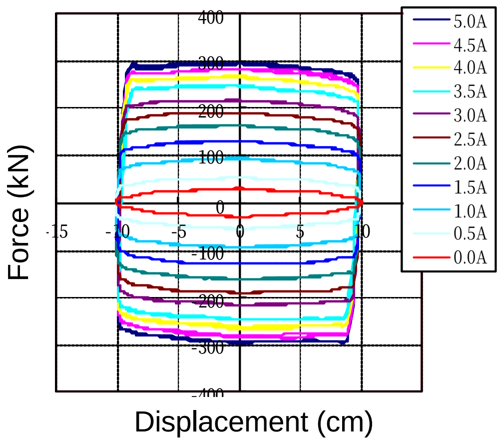


Fig. 5.9 Force-displacement Relationship of 400kN MR Damper

5.3.5 Conclusuions

Several kinds of MR dampers are developed. The damper with 20kN-capacity was developed to verify the performance. The 200kN and 400kN dampers were developed, which have the bypass flow piston. And the long stroke damper was developed for the base isolation building. The semi-active control by the MR damper is effective to reduce both displacement and acceleration responses through the large scale test model.

As results of this research, some future tasks are summarized.

1) Development of evaluation method of stability and durability of MR fluid.
2) Development of structure of MR damper for the effective use of MR fluid
3) Development of semi-active control strategy for the effective use of MR damper

5.4 Strain Induced Actuator

5.4.1 Research Objectives

Induced Strain Actuators (ISA) can change their own shapes according to external electric/magnetic fields, and vice versa. Recently these materials have been widely used for the small/precision machines because of some advantages from viewpoint of small sizes, rapid reaction, high power, high accuracy etc. The objectives in this study are to develop smart members for building and to realize the smart, comfortable and safe structures. The research items are as follows:

1) Semi-active isolation of structures using piezoelectric actuator
2) Using ISA as sensor materials
3) Improvement of Acoustic Environment

We will show some examples of application of ISA in this study.

5.4.2 Semi-active Isolation of Structures Using Piezoelectric Actuator

Using passive base-isolation technique, response acceleration of the superstructure is sufficiently reduced but large horizontal displacement between the ground and superstructure is needed. So to keep the margin space is necessary, but it becomes useless space when earthquakes do not attach the structure. In Japan, land prices are very expensive, so it is desired to make margin space smaller. In this study, semi-active base-isolation technique, which can reduce the acceleration of the structure and keep the margin space small, is adopted. Furthermore, semi-active system cannot supply energy to structure, so it is very safe system.

In this study, semi-active base isolation system with controllable friction damper using piezoelectric actuators is proposed. Two types of friction damper are proposed, one is holding type and the other is releasing type. (Figs. 5.10 and 5.11)It is better to use releasing type if we consider fail safe effect. By simulation study, it could be realized to reduce response displacement of the structure to 50% of values of the passive isolation.

5.4.3 Application of Piezoceramic Actuator to Active Noise Control

In order to improve the noise transmission loss of walls and windows, the conventional method of noise control often fails to reduce noise at low frequencies in particular. We experimentally confirm the practicability of the PZT to utilize for the secondary sources of the active noise control system.

As shown in Fig. 5.12, a loudspeaker is located inside the enclosure as a noise source and the opening was closed by an aluminum plate of 0.5mm thickness. PZT actuator is stuck on the middle of the aluminum plate. As a noise signal, a broad band noise of from 100 to 1kHz is radiated from the loudspeaker inside the enclosure. The deficiency of the transmission loss at around 125Hz is improved about 10dB by the active noise control.

5.4.4 Application of PVDF as A New Strain Gauge for Membrane

A key in membrane structure control is how to sense the stress state in the membrane. Measuring strain in membrane requires special technique since membrane has low stiffness. Ordinary wire strain gauges are generally too stiff and they

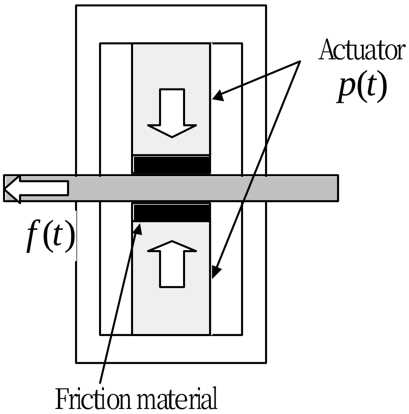


Fig. 5.10 Controllable Friction Damper (Holding Type)

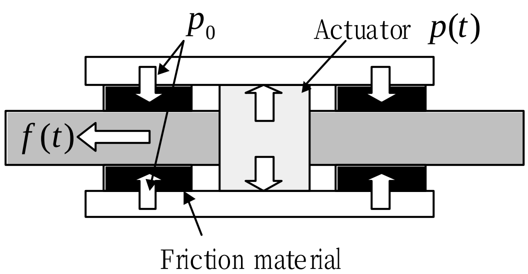


Fig. 5.11 Controllable Friction Damper (Releasing Type)

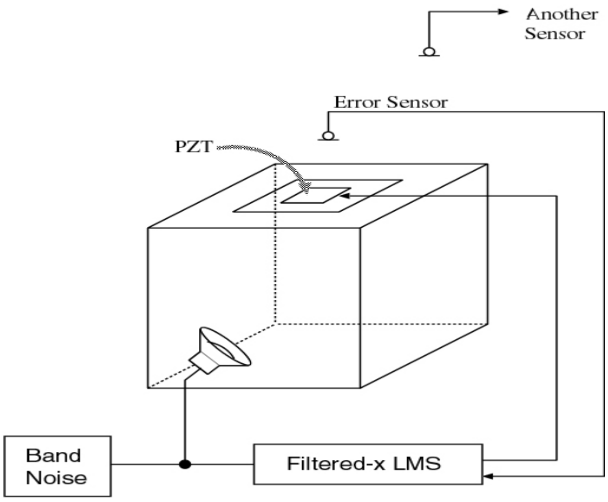


Fig. 5.12 Experimental Setup for Active Noise Control

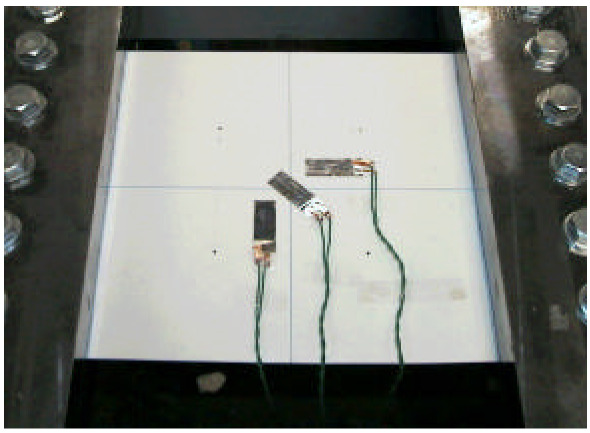


Fig.5.13 PVDF sensors for Membrane Specimen

violate the natural deformation state of the membrane.

In this paper we report the results of a series of tests aiming to develop a new flexible, low-stiffness, strain gauge for membrane using PVDF. Figure 5.13 shows experimental set up and the location of the sensors. Square grids were drawn on the membrane for the electric slide caliper. The strain rate was 6~8 me/sec, quasi static. For static strain sensor, slower static deformation process should be measured with same accuracy. For membrane strain sensor glue and gluing scheme which transmit the deformation of the membrane to PVDF without any reduction should be developed.

5.4.4 Conclusions

Research results are summarized as follows;

a) Semi-active isolation

As one of the methods to execute semi-active isolation of structures by smart structure, friction controllable damper using piezoelectric actuator was proposed in this study. Simulation study was carried out, and this damper is very effective to reduce response.

b) Active noise control

In this study, we indicate that PZT actuator can be used as the secondary source of the active noise control even for the broad band noise.

c) PVDF sensor

Low stiffness strain sensor for membrane, using PVDF, was proposed and two methods, open circuit and closed circuit, were examined.

5.5 High Performance Cementitious Composites

1.5.1 Research Objectives

The objective of this research is to develop high performance cementitious structural elements, which have highly energy dissipation and damage tolerant properties utilizing High Performance Fiber Reinforced Cementitious Composites (HPFRCC), to achieve a damage tolerant structural system as a smart structural system. Feasibility study will be conducted for the other types of cementitious smart materials, elements and systems. The self-repairable material is one of the research items. Guidelines for utilization of HPFRCC are final target of the research program.

5.5.2 What Is HPFRCC?

Figure 5.14 is an example of the flexural test of un-reinforced HPFRCC plate. HPFRCC is chopped fiber reinforced cementitious composites (mortar/concrete), which exhibits strain-hardening with superior strain capacity, shear ductility, and extreme damage tolerant mechanical behavior. The ultra ductile behavior of HPFRCC, combined with its flexible processing requirements, isotropic properties, and moderate fiber volume fraction (typically less than 2% depending on fiber type and interface and matrix characteristics) make it especially suitable for critical elements in seismic applications where high performance such as energy absorption, steel/concrete deformation compatibility, spall resistance and damage tolerance are required. Applications to both new structures and in retrofitting of existing R/C structures to withstand future earthquakes are considered.

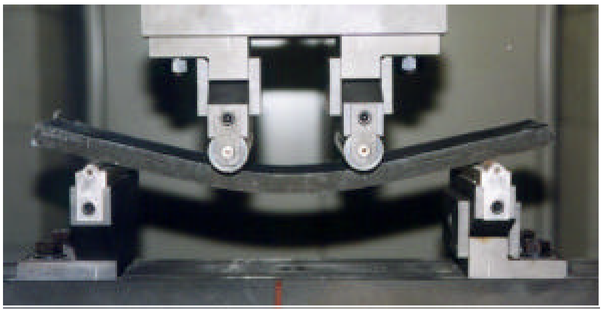


Fig. 5.14 Flexural Test of Un-reinforced HPFRCC Plate

5.5.3 Merit of Smart Structural System with HPFRCC

HPFRCC elements are expected to decrease the response and damage of building structures under external disturbances to achieve a high level of building performance requirements. Those requirements are not only structural safety but also reparability, serviceability, and durability of buildings after external disturbances.

The strength and ductility of the HPFRCC elements can be controlled easily by its dimensions and types of material used. Then it is expected to develop the suitable energy dissipation and damage tolerant elements for concrete structures with higher stiffness than the other types of structures. Since the HPFRCC elements will be able to dissipate the input energy by external disturbances even in the small deflection state of the buildings, response and damage of building will be decreased.

5.5.4 Research items and Results

Following research items have been investigated.

1) Development of HPFRCC materials, material design methods and clarification of its properties; There is an example of the tension properties of the developed HPFRCC, as shown in Fig. 5.15.
2) Development of the construction methods for HPFRCC elements
3) Development of HPFRCC constitutive model for FEM
4) Relationships between HPFRCC material properties and structural performance
    - Influence of tension properties of HPFRCC to the elemental performance
    - Influence of compression properties of HPFRCC to the elemental performance
    - Application into the HPFRCC damper for structural control is shown in the Figs. 5.16 and 5.17.
5) FEM analysis to investigate the relationships between material properties and structural performance
6) Feasibility study on the application example as HPFRCC damper, CES columns and self-repairing HPFRCC

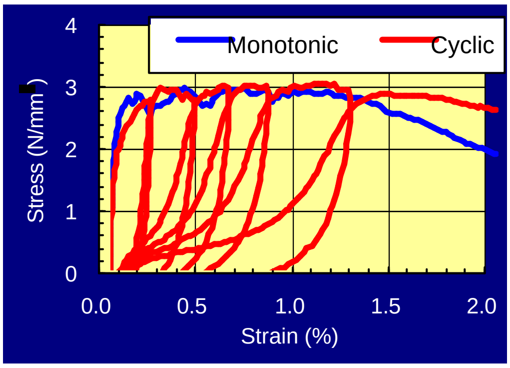


Fig. 5.15 Material Properties of Developed HPFRCC

Figure 5.16 Application example - HPFRCC damper for structural control

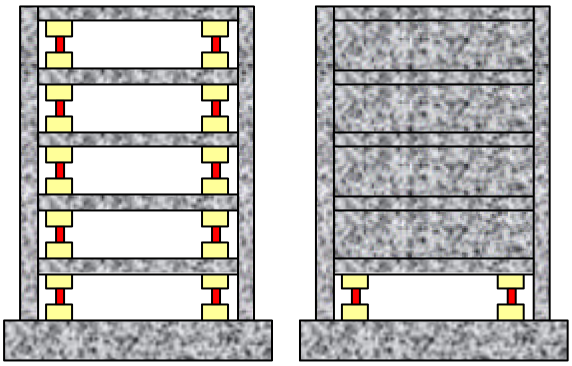


Fig. 5.17 Application examples of HPFRCC damper for R/C structures

5.5.5 Conclusions

The research results are summarized as follows;

1)The HPFRCC has high performance (very ductile) against tensile force through the material tests.

2)The strength and ductility of the HPFRCC elements can be controlled easily by its dimensions and types of material used.

3)The HPFRCC elements have highly energy absorbing characteristics

Actual application of the HPFRCC is highly expected to meet the variety of social requirements. The building regulation should be modified to support the development of the new technologies like HPFRCC materials and smart structural system with HPFRCC.

6 CONCLUDING REMARKS

Building Research Institute and the National Science Foundation, U.S.A. initiated the research and development of "Smart Structural Systems" in 1998 as a 5-year research project. The results of research are :

1) The concept of smart structural systems for building engineering was proposed.

2) Based on the concept of smart structural systems, new structural systems were proposed and developed.

3) The performance of proposed smart structural systems was examined. Especially, superior performances of rocking structural systems with yielding base plates and retrofit systems using loose linking elements were shown successfully by shaking table tests.

4) The performance evaluation guideline was proposed.

5) Some methods of system identification were tried and story damages and stiffness were detected.

6) Some newly developed sensors are tried to detect damages and some cracks or energy absorption were detected.

7) Sensor Network with RT-Linux is very useful for the monitoring system which requires the real time accuracy.

8) As materials which will be applicable in near future, following materials are selected;

+Shape memory alloys

+Electrorheological and magnetorheological fluids

+Induced strain materials

+High performance fiber reinforced cementitious composites

Characteristics of materials and these members and the applicability of these materials to building structures are investigated.

The MR dampers and Induced strain materials be applicable to response control through the semi-active control of buildings during earthquakes.

9) The MR dampers are effective to reduce the seismic response under an appropriate control.

10) The application of piezoceramic actuators to not only structural response control during earthquake but also Noise control for comfortable livings will be probable.

11) The HPFRCC will be applicable to damage control members of buildings.

12) The application of SMA to structural members in buildings will provide buildings will possess a self-restoration function.

Results of this program are summarized in annual report [6.1]~[6.5] of smart structural system published from BRI, BCJ, and et.al.. Report of 3 JTCCs and proceedings of workshop were summarized in references[2.1]~[2.3]. Forty-three papers in English are submitted as listed in Appendix.

This research and development project aims to apply advanced technologies, such as new materials and new structural systems, to develop smart structural systems. It is expected that the project can improve the performance

7 ACKNOWLEDGEMENT

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