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RESEARCH AND DEVELOPMENT ON SMART STRUCTURAL SYSTEMS IN U.S.-JAPAN COOPERATIVE STRUCTURAL TESTING PROGRAM

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ABSTRACT: The Building Research Institute (BRI) launched a 5-year research and development project on Smart Materials and Structural Systems in 1998 as part of U.S.-Japan cooperative research efforts. Smart Structural Systems also called as Auto-adaptive Media are defined as systems that can automatically adjust structural characteristics, in response to the change by external disturbances and environments, toward structural safety and serviceability as well as the elongation of structural service life. Smart materials and systems have been developed and studied.

Key Words: smart structural system, auto-adaptive, sensing and monitoring, sensor, actuator, shape memory alloy (SMA), magneto-rheological (MR) fluid, induced strain actuator (ISA), engineered cemetitious composite (ECC)

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 relatively large safety margin is provided for safety limit states taking into account various uncertainties in load and force amplitudes and structural response. Furthermore, since seismic design requirements have been improved through many lessons learned from the past earthquake disasters, the seismic performance of older buildings are usually inferior to that of new buildings as evidenced by the past earthquake disasters, e.g., the 1995 Kobe earthquake disaster. It is necessary to strengthen or replace those old buildings for the public welfare.

Smart Structural Systems are defined as structural systems 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 disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life (Otani 1999).

RESEARCH OBJECTIVES AND ORGANAIZATION

The research and development are carried out focusing on the following three thrusts.

1. Concept and performance evaluation: Several high-performance systems are developed, and the methods of performance evaluation are examined.
2. Sensing of structural performance: The damage detection methods, in which smart materials such as optical fibers, carbon fibers, shape memory alloys (SMA), and piezoelectric ceramics (PZT) are used as sensors, are investigated along with existing sensors, and the methods of system identification associated with damage detection are studied.
3. Development and performance evaluation of smart structural elements: Devices applying auto-adaptive materials such as SMA, PZT, magneto-rheological (MR) and electro-rheological (ER) fluids, high-tensile-strength and ductile concrete, and self-repairing material are developed.

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

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

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

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

The research organization is illustrated in Fig. 1. The Building Contractors Society, the Housing and Urban Development Cooperation, the Building Center of Japan, and many private enterprises have participated in this project.

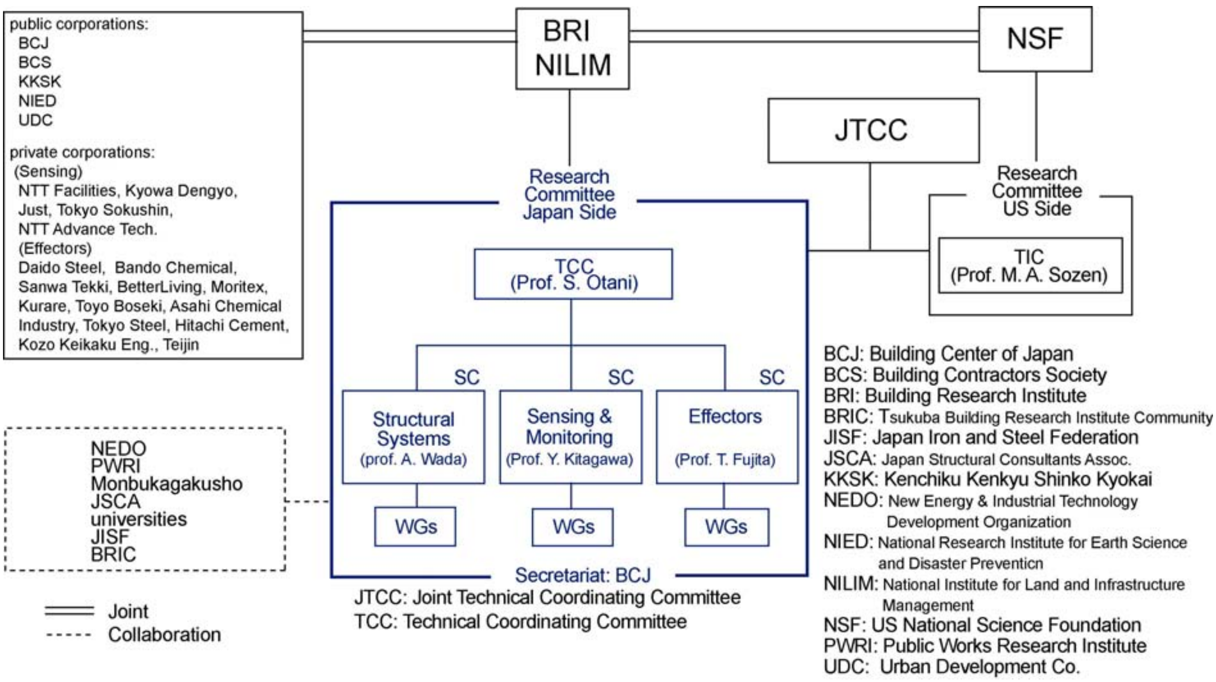


Fig. 1 Research organization on Smart Structural Systems

This research program started at 1998 as a five-year project. The research and development of (1) concept and performance evaluation methods of smart structural systems, (2) sensing of structural performance, and (3) development and performance evaluation of structural elements applying smart materials are conducted according to the timeline in Table 1. The accomplishments are summarized to the performance evaluation guidelines on smart structural systems (TCC 2003a), the application guidelines on sensors and monitoring (TCC 2003b), and the application guidelines of smart materials and members (TCC 2003c), through the large-scale tests for performance verification.

In the research period, the US-Japan Joint Technical Coordinating Committee (JTCC) meetings were held at Tsukuba and Hawaii in 2000, and at Tsukuba in 2002. The third JTCC meeting was held in conjunction with the workshop on smart structural systems (BRI 2002).

Table 1 Research timeline

	1998	**1999**	**2000**	**2001**	**2002**
Systems	Concept of smart structures				
		Proposals of smart structural systems		Large-scale tests	
				Performance evaluation guidelines	
Sensors	Survey of sensors		R/D of smart sensors		
	Survey and R/D of monitoring			Large-scale tests	
				Application guidelines	
Effectors	Survey of smart materials				
		Application to buildings		Large-scale tests	
				Application guidelines	

STRUCTURAL SYSTEMS

Introduction

The performance level required of building structures becomes higher and wider in recent years. A smart structural system is one of the solutions to realize the required 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, the authors try to apply the concept of smart structural systems to building structures. Some smart structural systems are developed based on this concept. The performance of smart structural systems is examined by numerical analyses and/or dynamic tests. Finally, the performance evaluation guidelines on smart structural systems are proposed.

Concept of Smart Structures for Buildings

The concept of smart structural systems was initially proposed in the field of aerospace engineering, where a smart structural system was defined as "a system that can detect damage, restrain damage propagation, actively control the response from external disturbance, and adapt its configuration to optimum state for the environment". The objectives and needs of smart structural systems for buildings are different from those of aerospace engineering, as shown in Table 2. 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 environments, toward structural safety and serviceability as well as the elongation of structural service life" (Otani 2000). We have focused on the studies in three types of smart structural systems based on this concept; auto-adaptive structural systems, reinforced concrete (RC) structural systems with damage fuses, and innovative life safety systems.

Table 2 Smart structural systems for aerospace and building engineering

	Aerospace engineering	Building engineering
Characteristics of structures	An airplane is originally active and adaptive.	A building is not required to be active or adaptive.
	An airplane has a simple usage and works as a single unit.	A group of buildings form a social unit with multiple usages.
External disturbance and required safety	A structure must be safe in daily use and disturbance.	A structure must be safe in rare events such as strong winds or earthquakes.
	Constant maintenance is required.	Free-maintenance is desirable.
Research needs	To integrate of smart functions into a structure to achieve light weight and high performance.	To put smart functions to a structure to achieve required performance such as minimum life cycle cost.
Typical example	Active control system	Health monitoring system

Development of Smart Structural Systems

Auto-adaptive Structural Systems

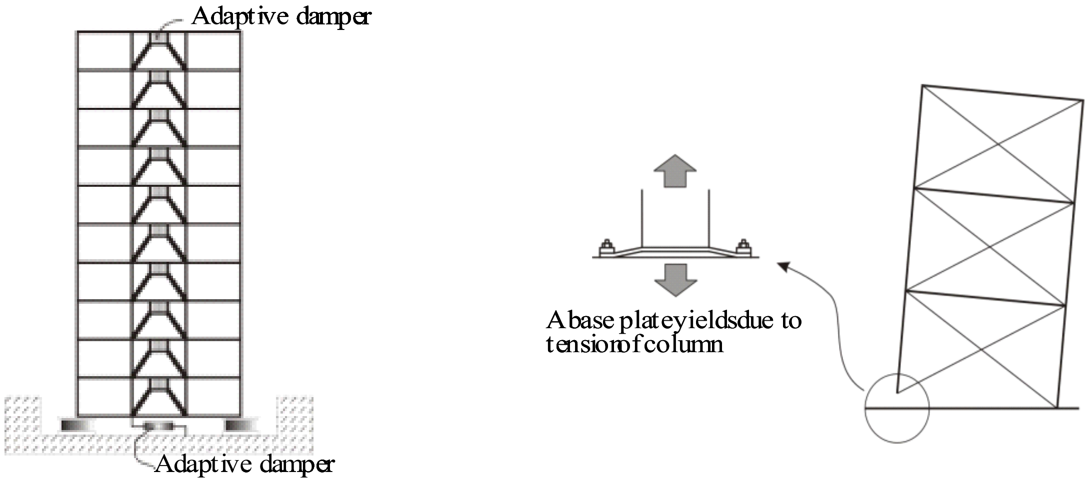
Auto-adaptive structural systems have auto-adaptive features using smart materials and/or smart systems. These systems are expected to possess the higher performance relying on the embedded functions of sensors, actuators and/or processors than the conventional structural systems. Two examples of these systems are shown in Fig.2. One is a hybrid system with semi-active response-control dampers made with smart material for the super-structure and seismic isolators. This system is able to reduce the 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 motion, the building causes rocking vibration automatically to reduce the 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 the test frames are shown in Fig. 3, whose base plates are shown in Fig. 4. From the test results, it is concluded that the base plate yielding systems are able to reduce effectively the seismic response of building structures (Azuhata 2002; Midorikawa 2003a, 2003b, 2003c).

RC Structural Systems with Damage Fuses

The example of RC structural systems with damage fuses is shown in Fig. 5. The damping effect of damage fuses such as dampers was examined. The seismic performance evaluation methods considering the damping effect have been developed. The evaluation methods are based on the capacity spectrum method (Kuramoto 2002), the energy input rate spectrum method, and so on.

Innovative Life Safety Systems

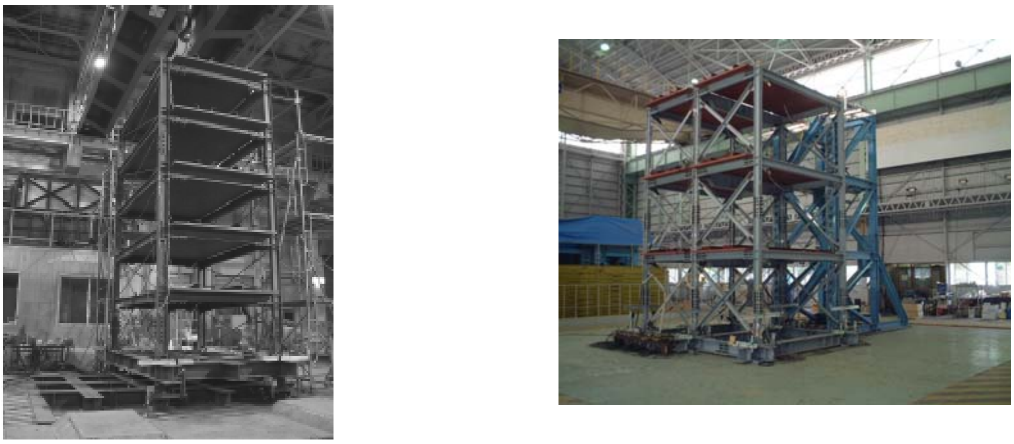
The simple and effective methods to improve the seismic performance of old low-rise buildings were studied. At first, we conducted a questionnaire survey to academics, graduate students and structural engineers. They showed us innovative ideas of new seismic elements and/or systems for life safety. The ideas were summarized into the following categories; 1) uplift of the base of a structure, 2) horizontal support of a structure, 3) a seismically isolated system, 4) an adaptive structure, and 5) a connecting system. Considering these results, we proposed innovative life safety systems easy to set up that apply loose linking elements. The concept of the system is illustrated in Fig. 6. The seismic response of this system was examined by numerical analyses and shaking table tests. Test specimen is shown in Fig. 7. From the results, the relation between the setup of the systems and its improvement effects have been made clear (Nakashima 2002).



(a) Hybrid system with semi-active response-control dampers

(b) Rocking structural system with yielding base plates

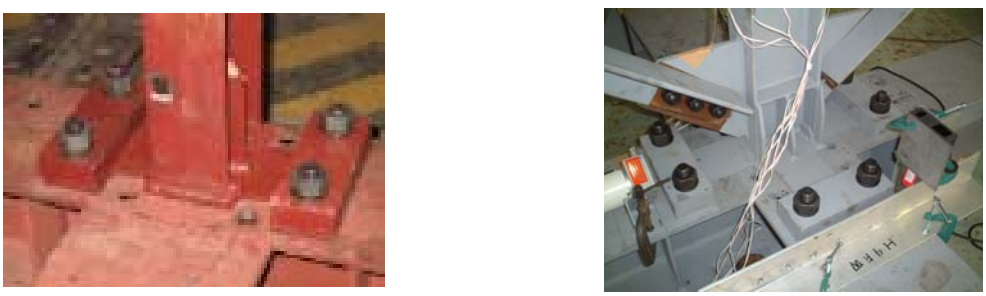
Fig.2 Examples of auto-adaptive structural systems



(a) Five-story test frame

(b) Three-story test frame

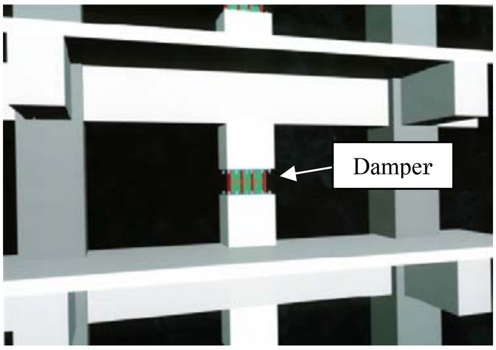
Fig. 3 Rocking frames for shaking table tests

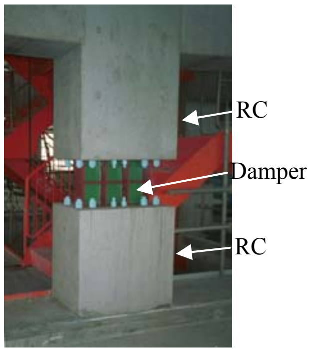


(a) Base plate with two wings of five-story test frame

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

Fig. 4 Two types of yielding base plates





(a) RC frame with dampers (b) Example of a damper

Fig. 5 RC structural systems with damage fuses

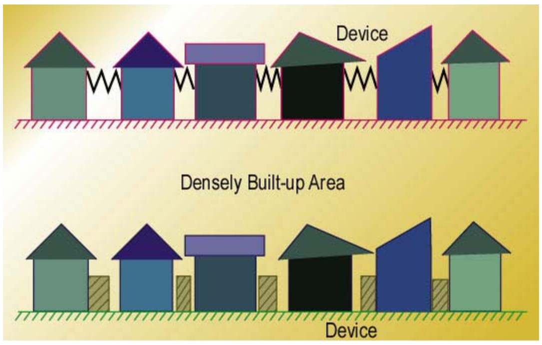
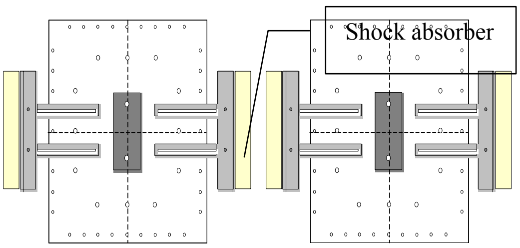


Fig. 6 Retrofit system using loose linking elements



(a) Plan of test specimen (b) Setup of test specimen

Fig. 7 Test specimen of retrofit system using loose linking elements

Performance Evaluation Guidelines

The contents of the performance evaluation guidelines (TCC 2003a) 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 these guidelines, 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 its life cycle cost.

Conclusions

1) The concept of smart structural systems for building engineering was proposed.
2) New structural systems as a smart structural system were proposed and developed.
3) The performance of the proposed smart structural systems was examined. Especially, the superior seismic performance 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 guidelines was proposed.

SENSING AND MONITORING TECHNOLOGY

Research Objectives of Sensing and Monitoring Technology

The objectives of the sub-committee of sensing and monitoring technology are;
1) To research and develop systems provided with sensors and processor or with sensors having their own processors, and,
2) To research and develop smart sensors.

The actual targets of research and development shown below are defined after having discussed among the members of the sub-committee. Then, the working groups have been organized in accordance with these targets.

The procedures of health monitoring (Teshigawara 2004) are shown in Fig. 8. In this project, we study the items in the inside of dashed line in Fig 8. The physical parameters from the measured data are evaluated.

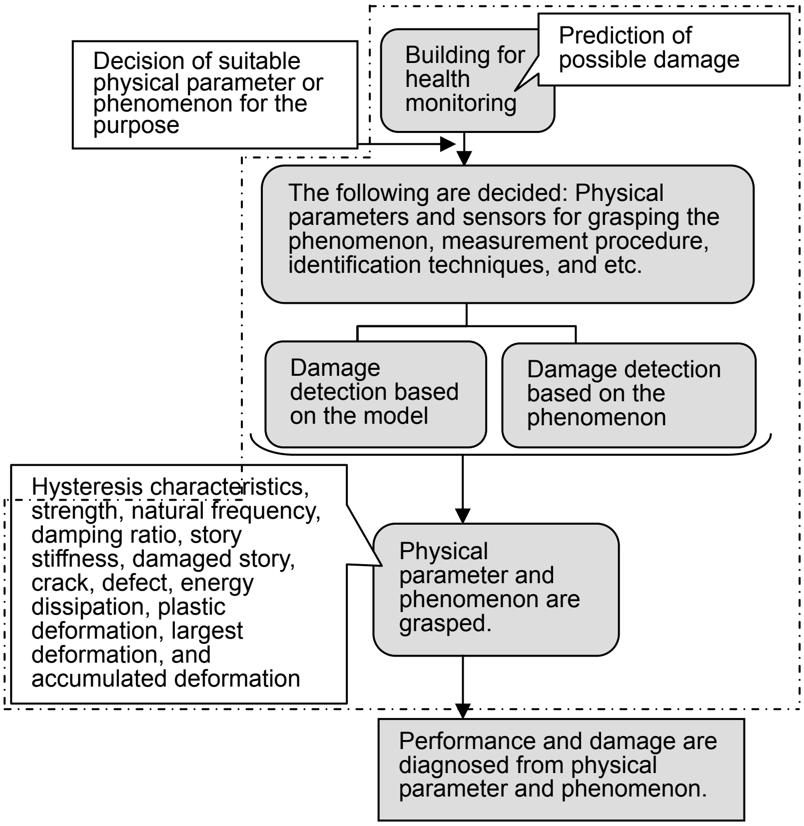


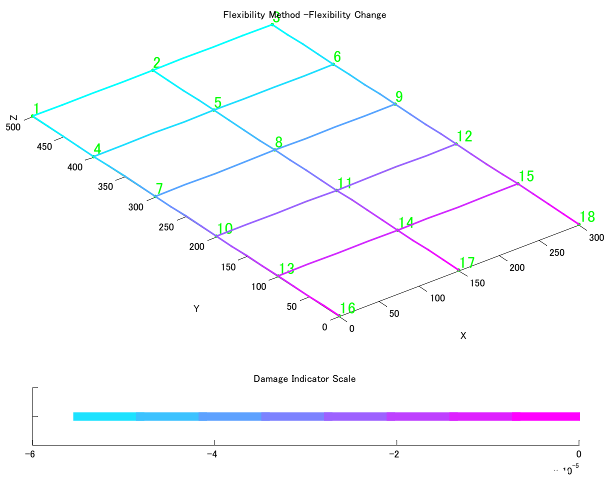
Fig. 8 Procedures of health monitoring

The accomplishments are summarized to the application guidelines on sensors and monitoring (TCC 2003b). But the way to evaluate the structural performance is not discussed in this guideline.

Structural Health Monitoring

Damage Detection Tests on Five-story Steel Frame

The damage detection tests on a five-story steel frame with the simulated damage are carried out (Morita 2001, Hamamoto 2002). The test frame is a five-story steel structure as shown in Fig. 9(a). The fiber brag grating (FBG) sensors, accelerometers, strain gauges and laser displacement meters are installed in the test frame. We assume the damage by removing the studs from only one story, loosening the high-tension bolts of beams, cutting the part of section of beams and/or removing the braces from only one story. We apply the flexibility method which is one of damage identification methods using modal properties. We apply this method to these experiments. In some cases we can estimate which story is damaged, and in other cases we cannot recognize the damage. If the studs at the first story are removed, the damage indicator of the first story is large as shown in Fig. 9(b). We also apply the method using multiple natural frequency shifts. Making use of the changes in five natural frequencies due to the damage, the location of damaged stories can be pinpointed. In both methods, we cannot identify the damaged stories in some cases. Some methods instead of the methods using modal properties have to be applied in such cases.



(a) Test frame (b) Flexibility changes for no studs at 1st story

Fig. 9 Damage detection tests on five-story steel frame

Damage Detection Tests on Large-scale Test Frame

The shaking table tests on a three-story large-scale steel structure with the cementitious devices are carried out (Morita 2003, 2004) at the large-scale seismic simulator facility of the National Research Institute for Earth Science and Disaster Prevention. The test frame is a three-story steel structure as shown in Fig. 10. The floor height of the test frame is 1.8 m, the total height is 5.4 m, the floor plan is 4m by 3m, and there are two spans in the transverse direction. The cementitious devices are installed in the central frame of the test structure and the devices are damaged during shaking. We carry out the damage detection tests using the devices and we measure the process of the damage. We apply the damage identification methods to these devices. Two types of identification methods are applied. One is a) the identification method using the data under excitation and the other is b) the identification method using the data obtained before and after the excitation. In both cases, we use the identification method of ARX model. From the identified results, the decrease of natural frequencies, the increase of damping ratios and the decrease of story stiffness as the experienced response amplitude or the input motion amplitude increases. The test results of story stiffness change are illustrated in Fig. 11. All characteristics estimated from the microtremor measurement are almost the same as those from the measurement by white noise shaking. A model using the stick-slip elements is proposed. The natural frequency, damping ratio and story stiffness described by this model are consistent with the experimental results.

Fig. 10 Large-scale test frame

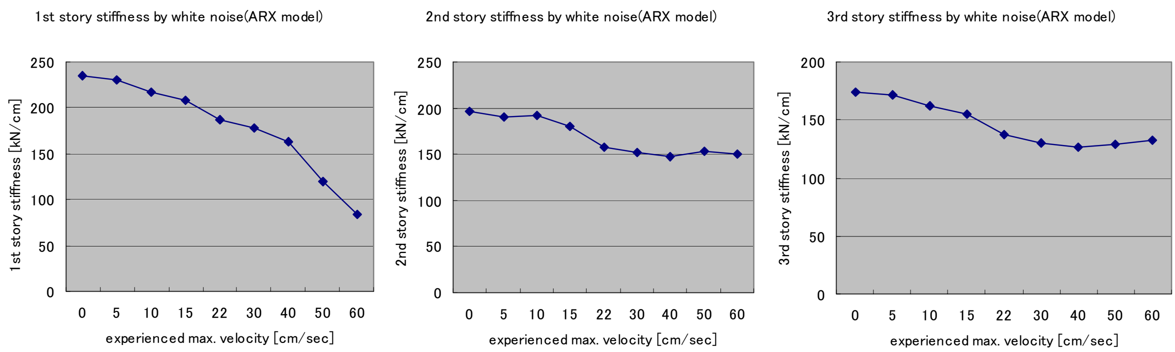


Fig. 11 Stiffness change according to experienced maximum velocity

Smart Sensors

Research Objectives

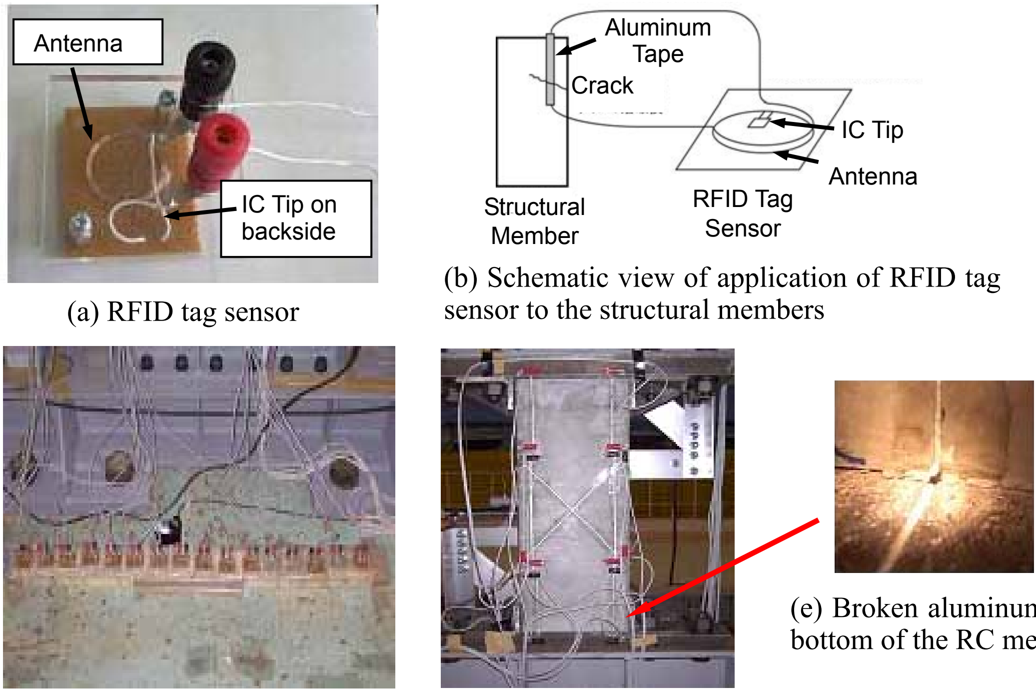
The research objectives of this study are to research and develop smart sensors that measure and identify the state and phenomena of building structures and structural members. Finally the guidelines for the application of smart sensors for health monitoring of building structures (TCC 2003b) are proposed.

Types of Sensors

Materials, equipment and systems that have the possibility to be used as sensors are surveyed, and the utilization and application of sensors are studied that have the higher feasibility for smart sensors. The following sensors are discussed in this study.
1) Optical fiber sensors for displacement, deformation, strain, heat, and water
2) Carbon fiber sensors in concrete for cracks, strain, and deterioration of concrete
3) Radio-frequency identification (RFID) tag sensors for cracks in concrete
4) Wave sensors for deterioration of concrete
5) Temperature sensors for plastic deformation of steel
6) Maximum value memory sensors for displacement, and,
7) Two-wire sensing system with processor-built-in sensors

Radio-Frequency Identification (RFID) Tag sensors

The original concept of this sensor was proposed by Prof. S. Wood of the University of Texas (Novak 2002). This sensor consists of an IC tip with a tag number and an antenna of which wire is elongated by additional wire, tape and carbon wire, as shown in Fig. 12. When a crack occurs in a structural member, the aluminum tape is broken and the RF transmitter and receiver cannot detect the RFID tag sensor. Only one RFID tag sensor detects the crack occurred at the bottom of the RC member and the other sensors cannot detect cracks, because most cracks are less than 0.04 mm in width and the aluminum tapes have too large ductility for crack detection. Therefore other wire materials such as small copper wires and carbon strings should be considered for crack detection.



(a) RFID tag sensor

(b) Schematic view of application of RFID tag sensor to the structural members

(e) Broken aluminum tape at the bottom of the RC member

(c) RFID tag sensors

(d) Aluminum tape for RFID tag sensor

Fig. 12 Application of RFID tag sensors

Two-wire Sensing Systems with Processor-built-in Sensors

The composition of the two-wire sensing system for the tests on a three-story steel frame is shown in Fig. 13. The system consists of 1) processor-built-in sensors, 2) two wires, 3) sensor controller, 4) two computers, and 5) wireless LAN system.

The processor-built-in sensor has an IC tip for strain measuring and an 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 gauges
2) 4 channels for on-off switch for crack detection
3) 8 bits accuracy of A/D conversion
4) 10 millisecond interval of A/D conversion
5) 64 words for memory
6) Memory for maximum and minimum values
7) Memory for local peak values (Fig. 14), and,
8) Two-wire link for electric power supply and communication with controller

Fig. 15 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 agreement. This sensor has no time information now, so we cannot get the time history but we can get the maximum and minimum values, each peak values and the accumulated values of data history.

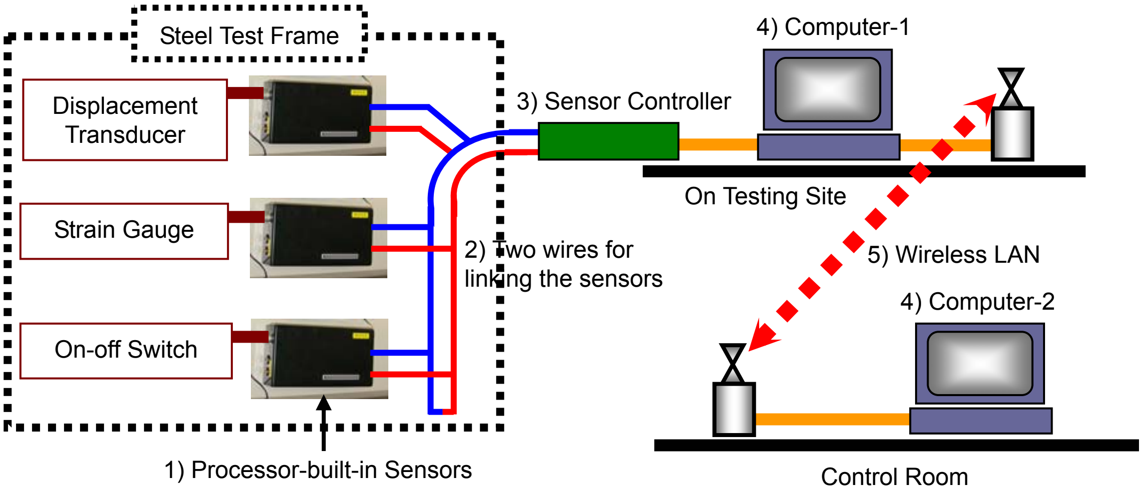


Fig. 13 Composition of wire-saving sensor system for three-story steel frame test

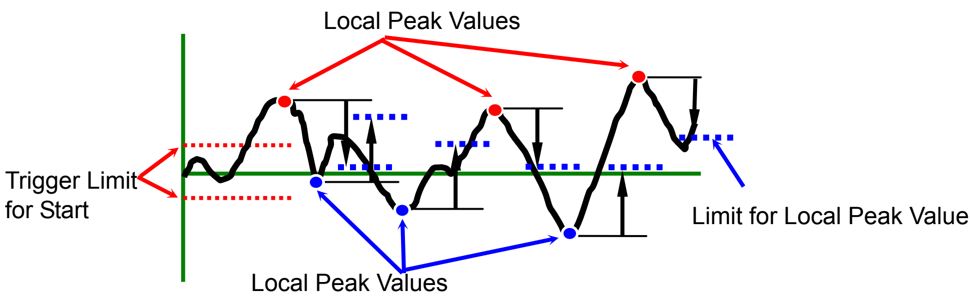


Fig. 14 Local maximum and local minimum values

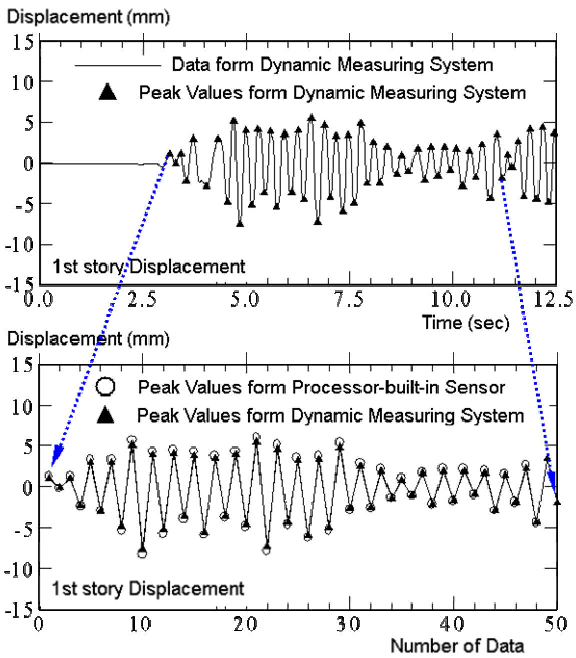


Fig. 15 Comparison of peak data obtained from dynamic measuring system and wiring-saving sensor system

Sensor Network Systems with RT-Linux

Introduction

As for the health monitoring which monitors the seismic performance of a structure, it is necessary to collect the data from various sensors installed in structural members and analyze them. The data collecting system is needed to achieve this concept.

In this section, the sensor network which connects the installed sensors and provides the health monitoring system of structures is studied. The fundamental items required for the sensor network is shown in the reference (Inukai 2000).

The following items including the experimental results are introduced below (Fig. 16(a)):

(1) Networked sensor systems
(2) Simultaneous measurement
(3) Real-time communication mechanism
(4) Utilization of existing infrastructure: Local area network, and,
(5) Necessity of real-time identification and diagnosis

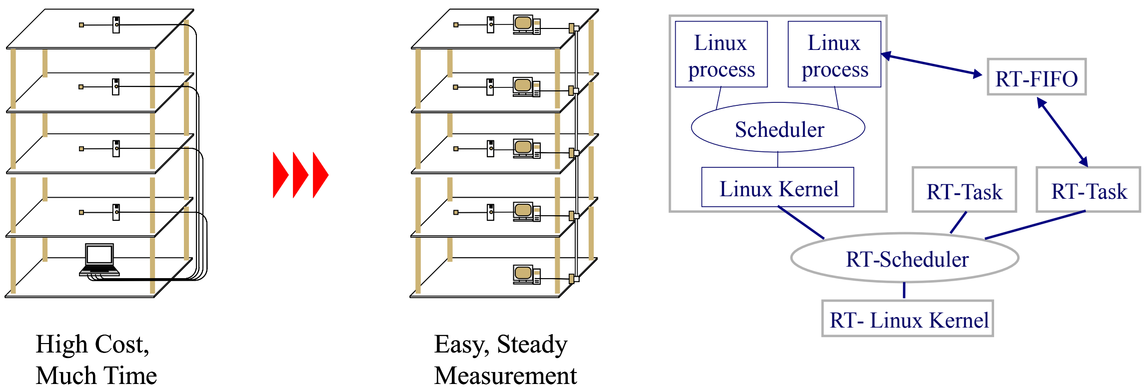
Sensor Networks

In these days, the information technology has made much progress, and local area networks (LAN) are installed in buildings, which connect each other. The sensor network is a measurement system of sensors installed at a part of LAN in these buildings.

The most important point in the sensor network is to have a real time accuracy between the measuring systems of sensors. The real time accuracy means the limited time between the start time of measuring and the end time of it. It is necessary to guarantee the same start time of measuring in all sensors and the same sampling time in the sensor network. That is why the sensor network uses RT-Linux which is an operating system (OS) with the function of the real time process. Fig. 16(b) shows the structure of RT-Linux. RT-Linux has an additional function to deal with the real time process in the high level priority among the kernel executed in OS.

The communication system in this sensor network uses RT-Messenger (Sato 2000, Yoshida 2002) which is the new real time application that works under RT-Linux.

In order to decrease the process for communication as little 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-Messager is defined as a packet type of RT-Messenger for receiving data of RT-Messenger from the data link layer.



(a) Utilization of LAN instead of wiring (b) Structure of RT-Linux

Fig. 16 Sensor network

Preliminary Experiments

The sensor network system is shown in Fig. 17(a). RT-Messenger is installed in three personal computers (PC). One PC is used as a server, and two PCs are used as slaves for receivers in the network. The PC properties are as follows: CPU; Pentium II 300, 400 MHz, Kernel version of Linux; 2.2.14, and RT-Linux version; 2.2.

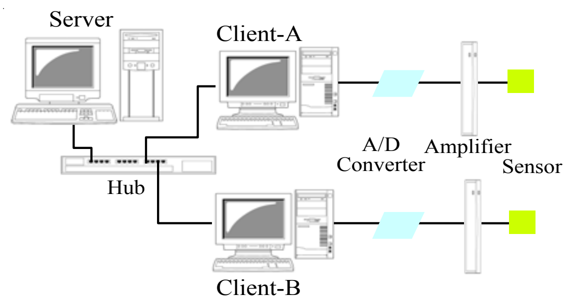
In order to test the real time accuracy of the sensor network, RT-Messages are served in the time interval of one millisecond from the server and the late times of serving in the server, and the late time of receiving in the Client-A and Client-B PCs are measured. As a result, the late time of serve is 1.3 microseconds in the maximum, and the late time of receive is 10.1 microsecond in the maximum. After the transmit command in the interval of one millisecond, the time interval of serve and receive is exactly measured in one millisecond. It means that the late time of serve and receive is short enough to the time interval. Consequently this sensor network has the enough real time accuracy.

In order to verify the effects of RT-Messenger, the performance between the system with RT-Messenger and the system without it are compared. The comparison method is that one PC serves a packet in the time interval of one millisecond from RT-Task and the other PC receives the packet on RT-Task. Fig. 17(b) shows the measurement results of the system with RT-Messenger. In the system without RT-Messenger at the side of the server, the ratio of which the time interval is one millisecond is about 10%, and the tolerance is larger. At the side of the receiver, the ratio of which the time interval is one millisecond is lower than 5%, and the tolerance is smaller.

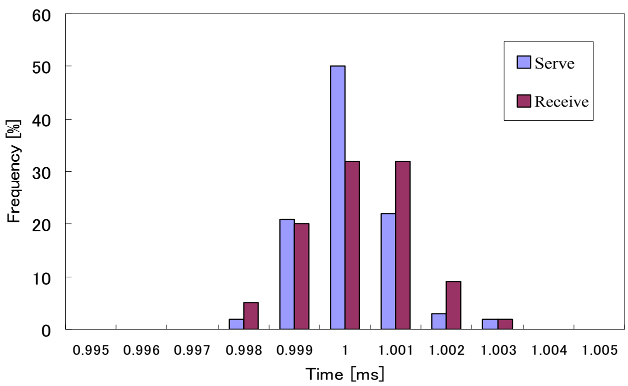
That is because the process interval time by the scheduler installed in Linux is guaranteed as at most ten milliseconds. RT-Linux is installed by the communication application called as RT-FIFO, but it works for the communication between RT-Task and the user process of Linux in one computer, and RT-Linux does not permit to communicate RT-Task between two computers directly. On the other hand, RT-Messenger permits to communicate RT-Task between two computers directly. As a result, RT-Messenger is necessary for sensor networks which require the real time accuracy.

Experiments in Large-scale Shaking Table Tests

The sensor network is applied to the large-scale test frame in the shaking table tests. In the shaking table tests, the natural frequencies in some modes between this sensor network and the FFT analyzer are compared. The comparison is also 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 the application to the tests, the proposed sensor network has enough real time accuracy.



(a) Sensor network system



(b) Time intervals with PT-messenger

Fig. 17 Experiments of sensor network

EFFECTOR TECHNOLOGY

Research Objectives of Effector Technology

The research objectives in the effector technology is to investigate the characteristics of several smart materials and the applicability of smart materials or members to building structures. According to the requests to be lighter materials, more effective and more reliable for the control techniques, smart materials are generally applied to systems in the aerospace fields. On the other hand, the application of smart materials to building use has hardly been accepted because of the necessity of a large amount of capacity and costs.

The smart materials which are applicable to building structures in the near future were selected as the research targets. Their characteristics and applicability are discussed herein.

The effector is defined materials and/or systems whose characteristics are adaptive, that is, changeable through external situation or external signals. These materials and systems apply forces to structures more effectively than those in the passive situation. In addition, the materials are included which make the structural performance higher during severe earthquake motions.

The following research items have been conducted:

i) Characteristics and application of the materials through summarizing the results in published references.

ii) Material characteristics are clarified through some fundamental tests.

iii) Devices and systems are proposed and tested for the verification as smart materials.

The materials studied are in the following:

a) Shape memory alloys

b) Electrorheological and magnetorheological fluids

c) Induced strain materials, and,

d) High performance fiber reinforced cementitious composites

The research results are summarized in the guidelines for the characteristics of materials and devices, and the applicable examples for buildings (TCC 2003c).

Shape Memory Alloys

Research Objectives

The shape memory alloys (SMAs) shows two properties; superelasticity and shape memory. These characteristics are dependent on the temperature in which SMAs are used as shown in Fig. 18.

The research is focused on the superelastic properties of titanium-nickel alloy, currently the most obtainable SMAs, to study their material properties as well as the application to building structures. In industrial products, SMAs demonstrate stable material properties; approximately 110 kN of titanium-nickel alloy is used to antennas for mobile phones in wire form every year, and it is also used to make eyeglass frames. In building construction, SMAs have been used in the form of tensile braces for seismic retrofit of historical buildings. All of the application have taken advantage of the superelastic properties of the alloy. In the wire form, the material is not only stable but has already demonstrated comparatively the high performance in terms of energy dissipation from cyclic loading. In this study, wires and bars were studied to determine the material properties of the alloy, with the aim of applying to building structures. And the potential of the application of the superelastic properties to control the structural response of buildings is examined.

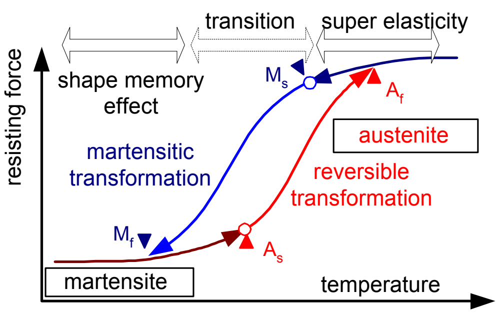


Fig. 18 Material phase-property-temperature relation of SMA

Research Results

The following results are obtained by the material tests of bar prototypes (see Figs. 19 and 20):

1) In the tensile tests, the material demonstrated the definite superelasticity within the strain of around 5% or less.

2) When the amount of dissipation energy from the cyclic loading is compared with wires and bars in the equivalent damping ratio, the value of bars is lower than that of wires.

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

4) The stress-strain properties under tensile strain are different from those under compression strain.

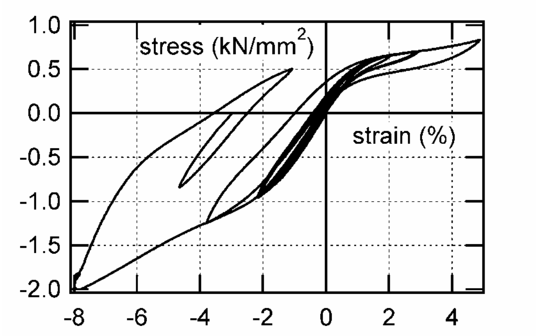
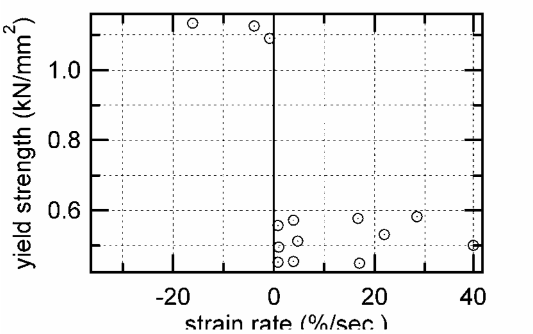
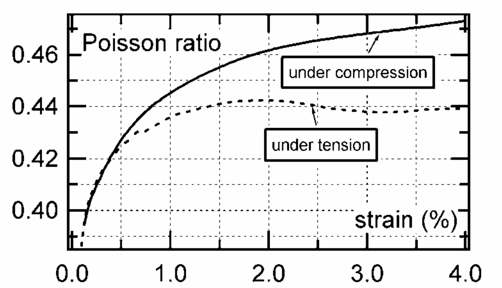


Fig. 19 Stress-strain relation of SMA bar



(a) Yield strength vs. strain rate

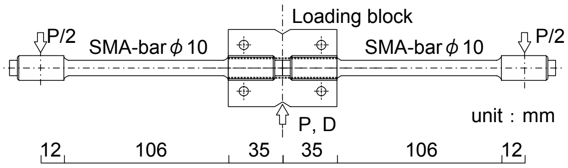


(b) Poisson ratio of SMA

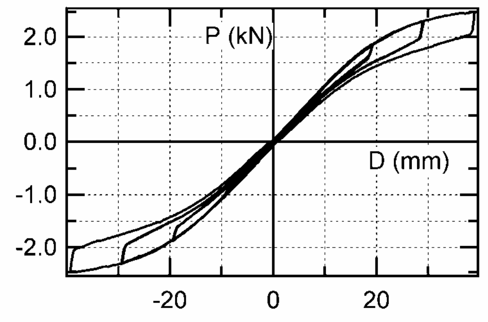
Fig. 20 Characteristics of SMA

Bars of the alloy are applied to tensile braces, bending members (see Fig. 21), anchor bolts for column bases, and connection bolts for beam-column joints. Wires are used as longitudinal reinforcements for reinforced concrete members (see Fig. 22) and tendons for prestressed members. These specimens for structural elements are tested to determine the potential of application of the superelastic properties to restore structural deformation to its original state, in other words, to determine the restoration performance. The results of these tests show that the members demonstrated the repair performance matching the material properties, and if the materials are used in a manner appropriate for the type, scale and etc. of the structure, they have the potential to demonstrate both restoration performance and energy dissipation. However, it is also learned that, even with the same alloy composition and method of manufacturing, bars have a lower degree of energy dissipation from cyclic loading under the superelastic condition. It is also learned that, in some cases, bars fracture brittlely under cyclic loading.

If SMAs are used for the response control of building structures, a member with the large restoring force capacity is needed. Accordingly, in the verification tests, bars are considered to be one of the possible solutions, and bars are used for tension bending members. Even with a bar form that has a large cross-sectional area, the improvement of the manufacturing process is desirable to enable great energy dissipation from cyclic loading and to ensure that the material never fractures in the early loading stage. In addition, the application of these bars must be designed to ensure the suitable control over the range of the applied stress and deflection.

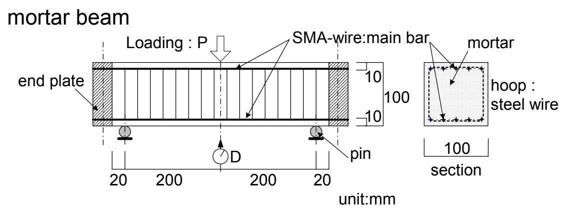


(a) Test specimen

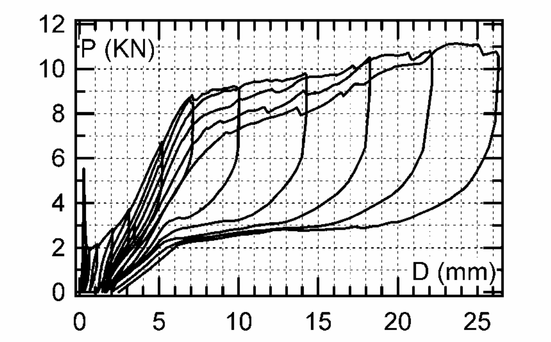


(b) Force-displacement relation

Fig. 21 Bending test on SMA bar



(a) Test specimen



(b) Force-displacement relation

Fig. 22 Bending test on cement mortar beam

Conclusions

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

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

Magnetorheological Fluids

Research Objectives

Magnetorheological (MR) fluids have the essential characteristics that change from free-flowing and linear-viscous fluid to semi-solid with controllable yield strength when exposed to the magnetic field. This fluid is an effective material for the development of controllable devices. It is intended to develop a structure that changes its damping characteristics to behave adaptively against seismic or wind forces and to achieve safety and functions by using MR devices with less energy.

Some researches on application of MR fluid by Spencer et al. were conducted at the beginning of this study. They developed a 200 kN MR damper (Spencer 1998) and proposed structural control strategies in the case of base-isolated (Johnson 1998) and fixed-base (Yi 1998) building structures.

Researches and Development of MR Fluids and MR Dampers

Magnetorheological fluid is the dispersion of fine magnetizable particles in a liquid medium. In order to improve the stability of dispersion, BRI and the research group have developed MR fluid *"#230"* with the enhanced stability (Fujitani 2003).

BRI and the research group have developed some MR dampers. At first, a simple MR damper (Fig. 23(a)) was developed in order to verify the performance of an MR damper, for example, the force-displacement relationship, the force-velocity relationship, the influence of temperature and response speed of an MR damper (Sunakoda 2000). Then a 200 kN MR damper was developed in order to verify the same items in the case that the electromagnet was attached to the bypass flow portion which was connected to the cylinder (Fujitani 2002a).

Next, a long stroke MR damper (Fig. 23(b): +/-295 mm)) was developed for a base-isolated structural model. The MR damper was used for the large-scale shaking table tests.

(a) 20 kN MR damper

(b) Long stroke MR damper

Fig. 23 Developed MR dampers

Performance Verification by Large-scale Shaking Table Tests

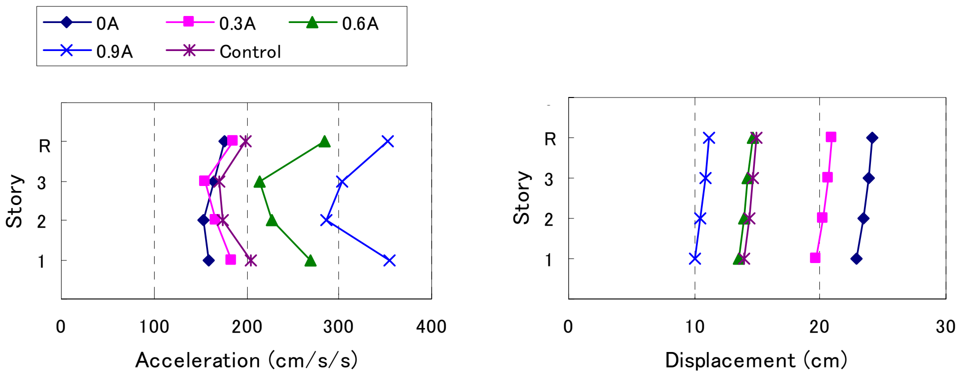
The semi-active control reduces both the response displacements and accelerations. An MR damper generates the damping force, which does not depend on the piston speed so much. The target of this study is to improve the safety, functionality and habitability by controlling the response displacements and accelerations by using MR dampers. For this purpose, a series of shaking table tests were conducted (Hiwatashi 2002).

Fig. 24 shows one of the test results. The controlled accelerations are reduced to the same values as those of the case of the constant electric current of 0.3 A, and the controlled displacements are reduced to the same values as those of the case of the constant current of 0.6 A. This shows that semi-active control by the MR damper reduces the response displacements while reducing the response acceleration (Fujitani 2002b).

Application to Actual Base-isolated Building

A 400 kN MR damper for an actual base-isolated building was developed and its dynamic characteristics were verified by the dynamic tests. The MR damper has 950 mm (+/-475 mm) stroke and the bypass flow piston. In order to verify the dynamic characteristics of the MR damper, a series of dynamic tests were conducted by using a dynamic actuator. Fig. 25 shows the force-displacement relationships. The yield force of the MR damper increases with the rise of the electric current. As a result, it is verified that the maximum damping force is controllable by adjusting the magnetic field

(Fujitani 2003).



(a) Absolute acceleration (b) Relative displacement

Fig. 24 Average values of response of each story of positive and negative sides
(1940 El Centro NS, Maximum velocity is 50cm/s)

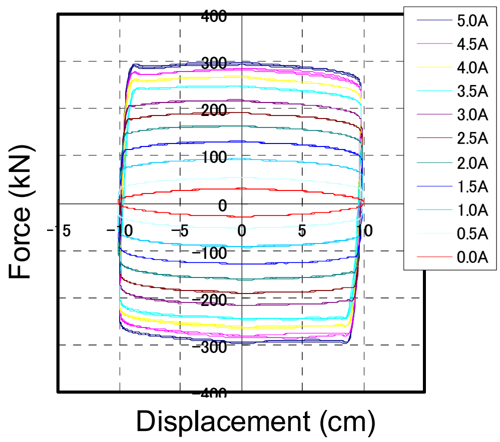


Fig. 25 Force-displacement relationships of 400 kN MR damper

Conclusuions

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

From the results of this research, some future tasks are summarized below.

1) Development of evaluation methods of stability and durability of MR fluids
2) Development of structure of MR dampers for the effective use of MR fluids, and,
3) Development of semi-active control strategy for the effective use of MR dampers

Induced Strain Actuators

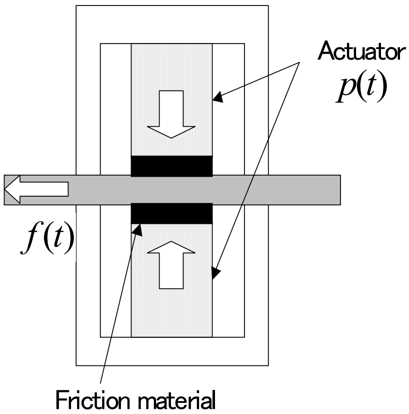
Research Objectives

Induced strain actuators (ISA) change their own shapes according to the external electric/magnetic fields, and vice versa. Recently these materials have been widely used for the small/precision machines because of some advantages including small sizes, rapid reaction, high power, high accuracy,

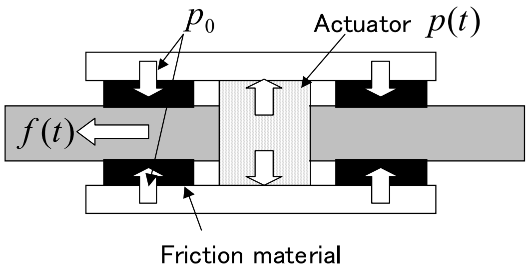
and etc. The objectives in this study are to develop smart members for buildings and to realize the smart, comfortable and safe structures. The research items are as follows:
1) Semi-active seismic isolation of structures using piezoelectric actuators
2) Use of ISA as sensor materials, and,
3) Improvement of acoustic environment
Some examples of the application of ISA in this study are shown in this section.

Semi-active Seismic Isolation of Structures Using Piezoelectric Actuators
Using the passive seismic isolation technique, the response acceleration of a superstructure is sufficiently reduced but the large horizontal response displacement between the ground and the superstructure occurs. Therefore, it is necessary to keep the boundary space between the superstructure and the retaining wall, but this space is useless when severe earthquakes do not attack the structure. As the land prices are very expensive in Japan, it is desired to make the boundary space smaller. In this study, the semi-active seismic isolation technique is examined which reduces the response acceleration of a structure and keeps the boundary space small. Furthermore, as a semi-active system does not supply energy to the structure, it is a very safe system.

The semi-active seismic isolation system with controllable friction dampers using piezoelectric actuators is proposed. Two types of friction dampers are proposed; one is a holding type and the other is a releasing type as shown in Fig. 26. It is better to use the releasing type if we consider the fail safe effect. From the results of the simulation study, it is concluded that the response displacements of the semi-active seismic isolation structure are reduced to 50% of those of the passive isolation system.



(a) Controllable friction damper
(Holding type)



(b) Controllable friction damper
(Releasing type)

Fig. 26 Two types of friction dampers

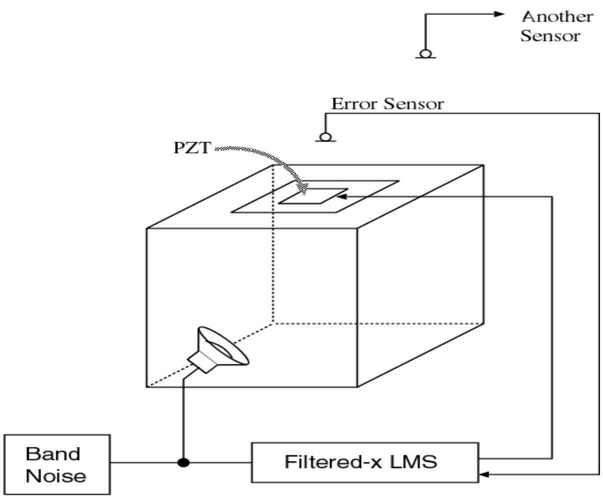
Application of Piezoceramic Actuators to Active Noise Control
In order to improve the noise transmission loss of walls and windows of buildings, the conventional method of noise control often fails to reduce noise in particular at the low frequency range. We experimentally confirm the practicability of PZTs to utilize for the secondary sources of the active noise control system.

As shown in Fig. 27(a), a loudspeaker is located inside the enclosure as a noise source and the opening is closed by an aluminum plate of 0.5 mm thickness. A PZT actuator is stuck on the middle of the aluminum plate. As a noise signal, a broad band noise from 100 to 1 kHz is radiated from the loudspeaker inside the enclosure. The deficiency of the transmission loss at around 125 Hz is improved about 10 dB by the active noise control.

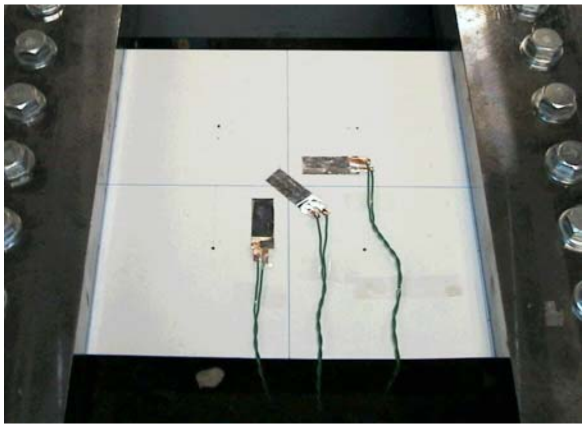
Application of PVDF as New Strain Gauges for Membrane

A key issue in the control of membrane structures is how to sense the stress state in the membrane. Measuring strain in the membrane requires the special technique since the membrane has low stiffness. Ordinary wire strain gauges are generally so stiff that they violate the natural deformation state of the membrane.

In this study, presented are the results of a series of tests aiming to develop a new flexible, low-stiffness, strain gauge for the membrane using polyvinylidene fluorides (PVDF). Fig. 27(b) shows the experimental set up and the location of the sensors. Square grids are drawn on the membrane for the electric slide caliper. The strain rate is 6 to 8 μ/s, that is, quasi static. For the static strain sensor, the slower static deformation process should be measured with the same accuracy. For membrane strain sensors the glue and gluing scheme which transmit the deformation of the membrane to PVDF without any reduction should be developed.



(a) Experimental setup for active noise control



(b) PVDF sensors for membrane specimen

Fig. 27 Application of PZTs and PVDF

Conclusions

The research results are summarized as follows:

a) Semi-active seismic isolation

As one of the methods to realize the semi-active seismic isolation of structures, a friction controllable damper using a piezoelectric actuator is proposed. From the results of the numerical simulation study, it is shown that this damper is very effective to reduce the seismic response of seismically isolated buildings.

b) Active noise control

It is indicated that PZT actuators can be used as the secondary source of the active noise control even for the broad band noise.

c) PVDF sensor

Low stiffness strain sensors for the membrane using PVDF are proposed and two methods: open circuit and closed circuit, are examined.

High Performance Cementitious Composites

Research Objectives

The research objectives are to develop high-performance cementitious structural elements, which have the high energy dissipation capacity and the damage tolerant properties applying high performance fiber reinforced cementitious composites (HPFRCC), to achieve a damage tolerant structural system. The feasibility study has been conducted for the other types of cementitious smart materials, elements and systems. The self-reparable material is one of the research items. The guidelines for the application of HPFRCC are the final targets of this study.

What Is HPFRCC?

Fig. 28 shows an example of the flexural test of an unreinforced HPFRCC plate. HPFRCC are the chopped-fiber reinforced cementitious composites (mortar/concrete), which exhibit the strain-hardening characteristics in the stress-strain relation with the superior strain capacity and shear ductility, and the extreme damage-tolerant mechanical behavior. The ultra ductile behavior of HPFRCC, combined with their flexible processing requirements, the isotropic properties, and the moderate fiber volume fraction (typically less than 2% depending on the fiber type, interface and matrix characteristics) makes them especially suitable for the critical elements in the seismic applications in which the high performance such as the energy dissipation capacity, the steel/concrete deformation compatibility, the spalling resistance and the damage tolerance are required. The applications to both new construction and existing RC structures to withstand future earthquakes are considered.

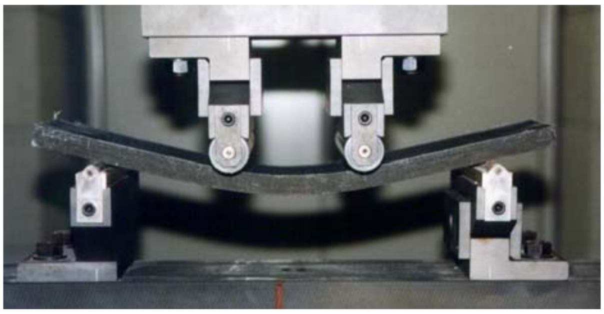


Fig. 28 Flexural test of unreinforced HPFRCC plate

Advantage of Structural Systems 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 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 HPFRCC elements are able to dissipate the input energy by external disturbances even in the small deflection state of buildings, the response and damage of buildings are reduced.

Research items and Results

The following research items have been investigated:

1) Development of HPFRCC materials, material design methods and clarification of their properties
An example of the tension properties of the developed HPFRCC is shown in Fig. 29.
2) Development of construction methods for HPFRCC elements
3) Development of HPFRCC constitutive models for the analysis by finite element methods (FEM)
4) Relationships between HPFRCC material properties and structural performance
Influence of tension properties of HPFRCC to the performance of structural elements
Influence of compression properties of HPFRCC to the performance of structural elements
Application examples of HPFRCC dampers for structural control are shown in Fig. 30.
5) FEM analysis to investigate the relationships between material properties and structural performance
6) Feasibility study on applications as HPFRCC dampera, CES columns and self-repairing HPFRCC

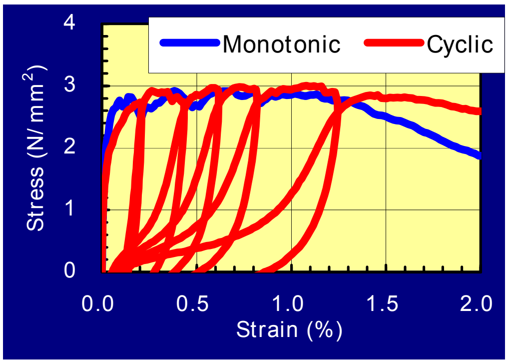
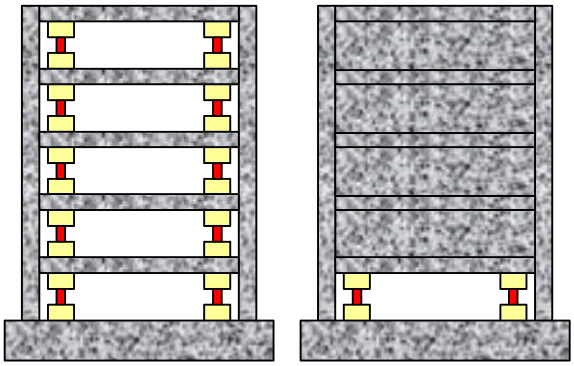


Fig. 29 Material properties of developed HPFRCC

(a) Example of HPFRCC dampers for structural control



(b) Application examples of HPFRCC dampers in RC structures

Fig. 30 Application of HPFRCC dampers

Conclusions

The research results are summarized as follows:

1) HPFRCC have the high performance (very ductile) against tensile forces from the results of the material tests.

2) The strength and ductility of HPFRCC elements are easily controlled by their dimensions and types of material used.

3) HPFRCC elements have the highly energy dissipating characteristics.

CONCLUDING REMARKS

The Building Research Institute and the U.S. National Science Foundation initiated the research and development on Smart Structural Systems in 1998 as a five-year research project. It is expected that the results of this research project will improve the structural performance of building structures.

The results of this research project are summarized as follows:
1) The concept of smart structural systems for the building engineering is proposed.
2) Based on the concept of smart structural systems, new structural systems are proposed and developed.
3) The performance of the proposed smart structural systems is examined. Especially, the superior seismic performance of the rocking structural systems with yielding base plates and the retrofit systems using loose linking elements are shown successfully by the shaking table tests.
4) The performance evaluation guidelines on smart structural systems are proposed.
5) Several methods of the system identification are applied to health monitoring of test building structures. From the shaking table tests, the story damage of test buildings can be detected.
6) Some newly developed sensors are applied to detect the damage of buildings. In the shaking table tests, some cracks or the energy dissipation of the test frames can be detected.
7) Sensor etworks with RT-Linux are very useful for the monitoring systems which require the real time accuracy.
8) The application of shape memory alloys (SMA) to structural members in buildings provides buildings with the self-restoration function.
9) The magnetorheological (MR) fluids dampers are effective to reduce the seismic response under appropriate control.
10) The MR dampers and induced strain actuators (ISA) are applicable to the structural response control through the semi-active control of buildings during earthquakes.
11) It is highly probable that piezoceramic (PZT) actuators are applicable to not only the structural response control during earthquakes but also the noise control for comfortable living.
12) High performance fiber reinforced cementitious composites (HPFRCC) is applicable to damage control members of buildings.

It is expected that these results improve the structural performance of buildings.

ACKNOWLEDGEMENTS

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