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Smart Structures and Materials 2000

Smart Systems for Bridges, Structures, and Highways

S.C. Liu
Chair/Editor

6-7 March 2000
Newport Beach, California

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SESSION 1

Smart Structure Technology Applied to Civil Infrastructure

Invited Paper

Development of Smart Systems for Building Structures

Shunsuke OTANI [a], Hisahiro HIRAISHI [b], Mitumasa MIDORIKAWA [b],
Masaomi TESHIGAWARA [b], Hideo FUJITANI [b], Taiki SAITO [b]

[a] Department of Architecture, University of Tokyo, Tokyo, Japan
[b] Building Research Institute, Ministry of Construction, Tsukuba 305-0802, Japan

ABSTRACT

Building Research Institute, Japanese Ministry of Construction, initiated 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. The U.S. Counterpart is the National Science Foundation. Smart Structural Systems (also called as Autoadaptive 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 extension of structural service life. The research and development of (1) concept and performance evaluation of smart structure system, (2) sensing of structure performance, and (3) development and evaluation of structural elements using smart materials will be conducted.

Keywords: Smart Materials, Smart Structural Systems, Autoadaptive Media, Sensing Technology

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 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 the Great Hanshin-Awaji 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 extension of structural service life.

The Building Research Institute (BRI), Ministry of Construction, Japan and the U.S. National Science Foundation (NSF) initiated the U.S.-Japan Cooperative Research Program on Autoadaptive Media (Smart Structural Systems) in 1998, under the aegis of the U.S.-Japan Panel on Wind and Seismic Effects of the U.S.-Japan Cooperative Program in Natural Resources. The First Joint Technical Coordinating Committee (JTCC) Meeting was held in Tsukuba, Japan, from January 6 through 8, 2000. At the meeting, research items and plans are discussed in detail corresponding to three research thrusts: (1) structural systems, (2) sensing and monitoring technology, and (3) effector technology.

This paper described the research items and plans of the research program in Japan based on the recommendations summarized at the JTCC meeting. To achieve 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 systems" chaired by Prof. A. Wada, Tokyo Institute of Technology,
- "Sub-committee on sensing and monitoring technology" chaired by Prof. Y. Kitagawa, Hiroshima University,
- "Sub-committee on effector technology" chaired by Prof. T. Fujita, Institute of Industrial Science, University of Tokyo.

2. CONCEPT OF SMART STRUCTURAL SYSTEMS FOR BUILDINGS

The concept of smart structural system was initially proposed in the field of aerospace engineering, however, structural systems for building engineering have different features from those for aerospace engineering as shown in Table 1. The value of a building should be determined not only by structural safety but also taking into account non-engineering points of

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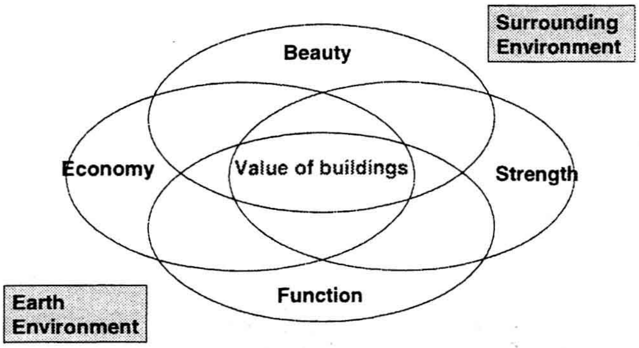

Figure 1 Evaluation Elements of Building

Table 1 Smart Structural Systems for Aerospace Engineering and Building Engineering

	Aerospace Engineering	Building Engineering
Characteristics of structure	Airplane is originally active and adaptive.	Building is not required to be active or adaptive.
	Airplane has a simple usage and works as a single unit.	A group of buildings form a social unit having multiple usage.
External disturbance and objective safety	Structure must be safe in daily usage and disturbance.	Structure must be safe in rare events, such as strong winds or an earthquake.
	Constant maintenance is required.	Free-maintenance is desirable.
Research needs	Integrate smart functions into a structure to achieve light-weight and high-performance.	Put smart functions to a structure to achieve objective performance such as minimum life cycle cost.
Typical example	Active control system	Health monitoring system

Table 2 Research Needs in Building Engineering

Category	Research needs
Function	Effective control of noise and vibration Creation of large open space without column and wall Design of highly irregular buildings Flexibility in building usage Extension of building life
Disaster prevention	Prevention of building or ground collapse Rehabilitation of old structures Damage detection of hidden structural elements Human safety at ultimate stage Repair of building damage Evaluation of seismic safety in urban environment Public education toward disaster mitigation
Environment	Protection of nature Control of environmental pollution Control of industrial waste Reduction of dust and noise during construction
Production	Countermeasures against shortage of expert builders Improvement of construction quality High speed construction Development of new material

view such as "beauty", "economy", and "function." Therefore, in the first stage of research project, the objectives and needs of smart structural systems for building engineering should be clarified. Table 2 summarizes the research needs of a smart structural system for buildings.

Based on the conceptual study of smart structural systems for buildings, the following items are selected as research targets for the sub-committee on structural systems (chaired by Prof. A. Wada, Tokyo Institute of Technology).

(a) Autoadaptive structural systems
- Proposal of feasible structural systems with autoadaptive features
- Integration of smart materials or devices / members to achieve target performance of structural systems
- Investigation of the proposed structural systems by computer or experimental simulations
- Establishment of performance evaluation guidelines for structural systems with autoadaptive features

(b) Reinforced Concrete (RC) structural systems with damage fuses
- Examination of performance based design/ assessment methods
- Selection of damage-control devices and damage-sensor systems
- Development of performance based design/ assessment methods
- Development of repairing/ replacing techniques for damage-control devices and damage-sensor systems

(c) Innovative life safety systems
- Survey of causes of collapse of traditional light construction
- Proposal of innovative life safety systems for traditional light construction
- Investigation of proposed systems* by computer and experimental simulations
- Establishment of performance guidelines for life safety systems in traditional light construction

* such as using aluminum alloy window frames, reinforced sliding doors, the air-bag system and support frame systems.

3. SENSING AND MONITORING TECHNOLOGIES

3.1. Objectives

The purpose is to identify research needs for developing new sensing systems, which consist of advanced sensors and procedures for data collection, management, and interpretation. Research is needed to develop new types of sensors and obtain information about the long-term viability of the sensors. The sensor is one part of smart building structures, which include sensors, effectors, and processors.

Highly-reliable monitoring systems which combine various advanced sensors with system identification and damage diagnosis techniques are required. The monitoring systems must be able to pinpoint the location and determine the extent of the damage for different types of structural systems.

3.2. Research Items

Items of research and development on the issue of sensing and monitoring technologies are described below.

1) Sensor technology
- New sensors should be wireless, portable, self contained, capable of discriminating among different types of data, and subjected to environmental testing.
- New sensors are needed to detect cracks, to monitor stress, strain, corrosion potential, and temperature.
- Innovative technologies, such as MEMS, should be considered for new sensing devices.

2) Monitoring and Damage Assessment
- Monitoring technologies that integrate the output from global and local sensors are needed to identify damage in real time.
- New algorithms are needed to quantify the extent of damage from ambient vibration measurements and external excitation.
- Software for efficient signal processing and integration of data from various sensors must be developed.
- Evaluation strategy of structural performance for incorporation into smart structural systems is also required.

3) Networking
- Integration of network systems to evaluate data from multiple structures throughout a city is required.
- Because the life of the sensors is expected to be longer than the life of current computer systems or software, the interface between sensors and monitoring systems must be flexible.

3.3. Current Activities

Ongoing research plan in the sub-committee on sensing and monitoring technology (chaired by Prof. Y. Kitagawa, Hiroshima University) are classified into two subjects. One is defined as structural health monitoring system. The other is networking systems integrated with sensors. Current activities of two subjects are shown below.

1) Experimental test for structural health monitoring systems
The main target of health monitoring systems is to detect damage parts and evaluate present structural performance. A five-story steel frame with approximately one-third scale (as shown in Figure 2) was built to examine various damage detection methods. Structural damage is simulated by removing members or changing member properties in localized region. In addition to the conventional sensors to measure floor displacements and accelerations, optical fiber sensors are put on the surface of members to detect local deformations. Using these sensing data, several damage detection methods such as the method using vibration mode shapes are applied to evaluate the simulated damage and the limitation and improving points of the methods are examined.

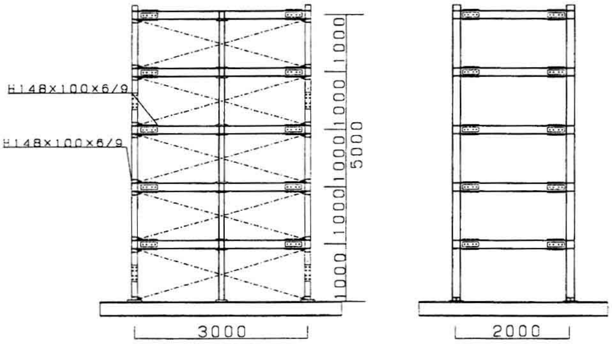

Figure 2. A five-story steel frame model (unit: mm)

2) Concept of sensor networking systems
It is recognized that integration of network systems to evaluate damage data of structures throughout a city is essential to identify damage regions and make necessary countermeasures. The networking systems can be classified into three scales; a system for a single building, a system to cover several buildings in a block, and a system to cover all buildings in a city. The sensor network system should be equipped with database of structural information such as design drawings. Also, the system should utilize effectively the up-to-date information technologies such as wireless data transportation using mobile phones and satellite image, virtual reality techniques to visualize damage situation, high speed internet for data transfer, etc.

4. EFFECTOR TECHNOLOGIES

4.1. Objectives

The purposes are to develop smart materials and smart devices, and to verify that they can effectively control responses of structures and increase the safety and serviceability of structural systems, and disaster recovery. At the first stage, characteristics of smart materials and devices will be investigated. By relating these characteristics to their applications, methods of implementing this technology will be evaluated, e.g. suitable placement, required capacity, effective use, etc. , so that engineers can design more damage tolerant structural systems.

4.2. Research Items

Items of research and development on the issue of effector technologies are described below.

1) Smart materials and devices

The following smart materials and devices are mainly considered.

- Shape memory alloys
- Controllable fluids (e.g. electro-rheological and magneto-rheological fluids)
- Electro-strictive elements (e.g. piezo-ceramics) and magneto-strictive elements
- High-performance cementitious composites (HPCC)

2) Assessment of the applicability and efficacy of smart materials to structural systems

- Large scale prototype and components for auto-adaptive devices and smart material components should be developed and evaluated.
- This process should entail large scale testing on devices, on shaking table systems, and with pseudo-dynamic methods.
- The result of this testing should be used to determine dynamic mechanical properties of auto adaptive devices and smart structural components, and of the overall structural performance of complete auto adaptive systems.

Corresponding to the listed four smart materials, four different working groups were formulated under the sub-committee on effector technology (chaired by Prof. T. Fujita, Institute of Industrial Science, University of Tokyo).

4.3. Current Activities

4.3.1. Shape memory alloys (SMA)

Shape Memory Alloy (SMA) shows three different characteristics depending on the temperature; shape memory effect, pseudo elasticity and partial pseudo elasticity. The objectives of this study are to utilize SMA for the smart structural members in order to realize the smart structural system in buildings. Some SMA devices will be developed for these purposes, and the guidelines on SMA for structural design will also be summarized. The current activities of the SMA working group (chaired by Prof. Y. Kitagawa, Hiroshima University) are described below.

1) Survey on properties and current application to buildings
General properties of SMA compounded of nickel and titanium were surveyed using references; shape memory effect and pseudo elasticity, transformation temperature, general stress-strain relation and its strain rate were quantitatively grasped. Especially, it was found to be important to apply the SMA to structural members of buildings that the stress-strain relation depends on the transition temperature, number and amplitude of cyclic loading, strain rate, and surrounding temperature. At present, it is very difficult to weld SMA with other metals, but it is possible to use mechanical joints because SMA can be drilled, cut and sliced. Table 3 summarized some examples of application of SMA in Japan.

2) Test of SMA specimens
The required specification of SMA specimens was selected to be a wire and a bar with pseudo elasticity under room temperature (around zero to 30 degree centigrade). The casting variables are reduction ratio at the cold forming and heat temperature for shape-memory. Some specimens were produced under the combination of these variables and examined to compare their stress-strain relation in tension. A part of test results is shown in the Figures 3 and 4. A wire with 30% of reduction ratio shows good pseudo elasticity under room temperature. Especially the treatment under 550 degree centigrade heat and quench was found to give a fine pseudo-elasticity to the wire specimen. Bars with 16.5mm of diameter will be shaped without cold form process and be memorized with controlling heat and quench because of the production lines.

3) Cutting and shaping of SMA bars
The various conditions of cutting external threads and shaping SMA bars were examined. The bits for normal carbon steel such as SS400 of JIS (Japan Industrial Standard) were found to be unsuitable for SMA bars. Now, the bits for hard metals are tested to cut and shape the SMA bars.

Table 3 Examples of application of SMA in Japan

Properties of SMA	Examples of application
Shape memory effect	Control of room temperature using SMA sensors and actuators Door unlock system for earthquakes using SMA actuators Deflection control of structure using SMA wires Stress control of pre-cast concrete members using SMA springs Demolition of a part of concrete structures using SMA devices Joints of steel pipes using SMA tubes Framework of reinforced concrete curved membranes using SMA supports
Pseudo elasticity	RC members with longitudinal bars of SMA Isolation system of containers for vibration Base isolation device with the combination of SMA, rubber and lead Seismic energy absorbing device for historic structures or bridges

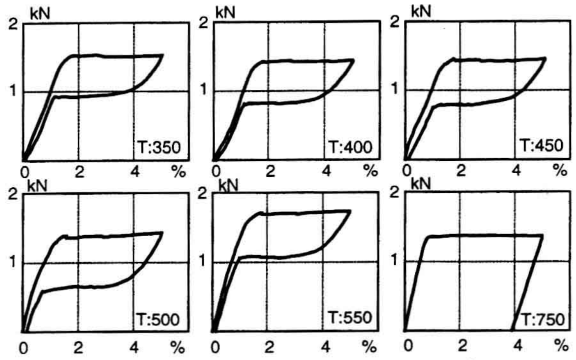

Fig. 3 Stress-strain relations of specimens under deferent temperatures at shape memory treatment (cf. test condition : in room temperature)

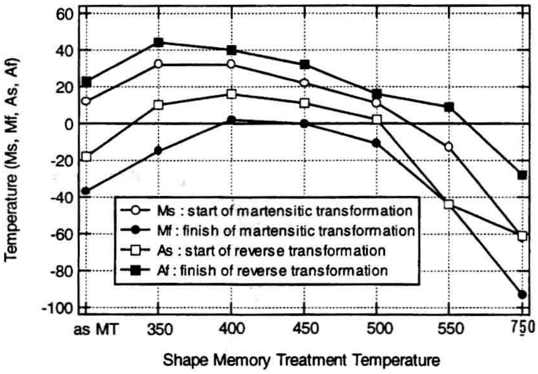

Fig. 4 Transformation temperature vs. shape memory treatment temperature of SMA

4.3.2. Controllable fluids (e.g. electro-rheological and magneto-rheological fluids (ER/MR))

Electro/Magneto Rheological (ER/MR) Fluids have essential characteristics that change from free-flowing, linear viscous fluid, to a semisolid with a controllable yield strength in milliseconds when exposed to an electric and magnetic field. These fluids are effective materials for development of controllable devices. It is intended to develop a structure that changes its stiffness and damping characteristic to behave adaptively against earthquake or wind forces and achieve safety and functions by using ER/MR devices with less energy. The research items of the ER/MR working group (chaired by Prof. S. Soda, Waseda University) are described below.

1) Quantification of mechanical characteristics and material properties of ER/MR fluid
The mechanical characteristics are investigated using MR fluids developed and the required performance of new MR fluids is discussed.

2) Performance evaluation and development of ER/MR devices
The mechanical characteristics of ER/MR devices are investigated by experimental tests of ER/MR devices which are available on the market and the performance evaluation method and the required performance of ER/MR devices are discussed.

3) Development of adaptive structures using ER/MR devices
Ideas of adaptive structures using ER/MR devices are summarized and their effectiveness will be verified by numerical simulations and real-scale experimental tests. The evaluation method and design method of adaptive structures will be discussed. Examples of application of ER/MR devices are presented in Figures 5 and 6.

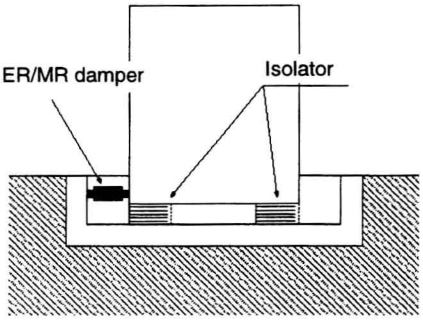

Fig. 5 Base-isolated structure controlled by ER/MR devices

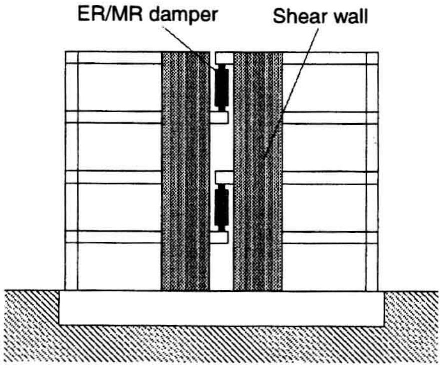

Fig. 6 Control of flexural behavior by ER/MR devices

4.3.3. Electro-strictive and magneto-strictive elements

Electro/magneto-strictive elements (induced strain actuator (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. Designing guidelines of ISA materials/devices are also discussed. The research items of the ISA working group (chaired by Prof. T. Fujita, Institute of Industrial Science, University of Tokyo) are described below.

1) Development of smart structural members using ISA devices
ISA materials are very suitable for structural control. We try to integrate these materials into normal structural members such as columns, beams etc. to realize smart structural systems. Example images are shown as Figures 7 and 8.

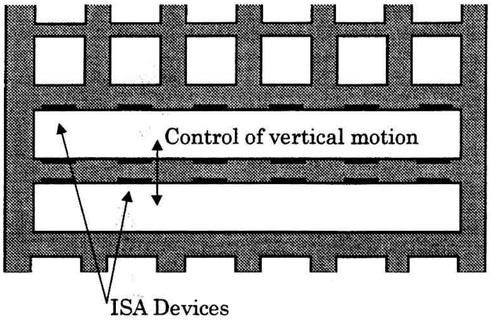

Fig. 7 Active control of floor vibration

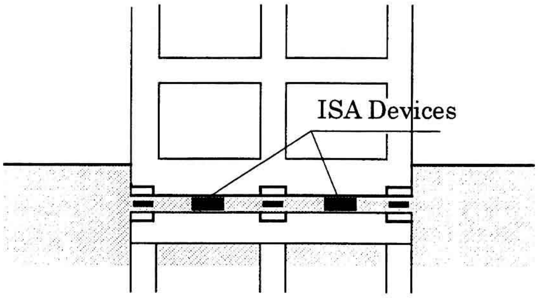

Fig. 8 Friction control for base isolation

2) Using ISA as sensor materials
ISA materials can act as sensors because they cause change of electric or magnetic fields under deformation (see Figure 9). As schematically shown in Figure 10, PVDF (Polyvinylidene fluoride) sensors are suitable for membrane structures.

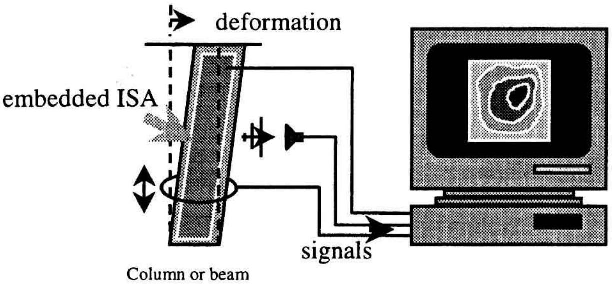

Fig. 9 Sensing system with or without cabling

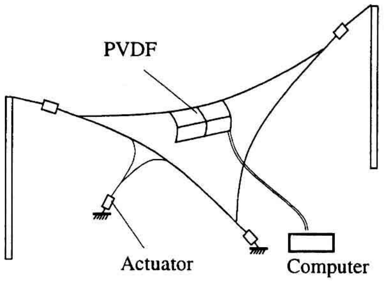

Fig. 10 PVDF sensors for membrane

3) Improvement of Acoustic Environment
Polymers based ISA films or distributed ISA devices can control vibration mode of plane members. Applications to music halls or dwelling partition walls are expected. Experimental study of noise control is now planning.

4.3.4. High-performance cementitious composites (HPCC)

HPCC is chopped fiber reinforced mortar/concrete micro-structurally designed using micro-mechanical principles. HPCC exhibits strain-hardening with superior strain capacity, shear ductility, and extreme damage tolerant mechanical behavior. The ultra ductile behavior of HPCC, 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,