DEVELOPMENT OF SMART STRUCTURE SYSTEM

by

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ABSTRACT

Building Research Institute, Ministry of Construction (BRI) has started the research and development of " Smart Structure Systems " cooperated with National Science Foundation, U.S.A. in 1998. Smart Structure Systems are defined as the systems that can appropriately respond the change of external disturbance and can reduce the safety margin for the safety design, improve the serviceability, and make the building life long. 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 will be conducted.

KEY WORDS: Smart structure system, Health monitoring, Shape memory alloys, E/M rheological fluids, Induced Strain Actuators, Engineered cementitious composites

1. INTRODUCTION

Structure Systems in the past had chosen and constructed materials and framing system in order to achieve the intended function toward an expected loads and forces. It was undoubted that the existing system could not give full play to its ability to cope with an unexpected loads and forces. And a large safety factor at the safety design stage was needed to avoid the risk. Strengthening and a removal of existing buildings, which had problems in their safety, was also required. It was confirmed by the damage of HYOGO ken Nambu Earthquake. Here, Smart Structure Systems is defined as a structural system with a certain-level autonomy such as sensors, actuators and processors, which can appropriately respond the change of external disturbance and can reduce the safety margin for the safety design, improve the serviceability, and make the building life long.

2. TARGET ISSUES AND RESEARCH ORGANAIZATION

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

(1) Concept and performance evaluation method of smart structure system. In this research issue, Auto-adaptive system and high-performance system be developed are proposed, and performance evaluation method will be proposed.

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(2) Sensing of structure performance. In this issue,damage detection technology using sensors utilizing smart materials, such as optical fiber, carbon fiber, shape memory alloy, PZT as well as existing sensors, and system identification method are proposed. And,

(3) Development and evaluation of structural elements using smart materials. In this issue, devices utilizing the auto-adaptive material such as shape memory alloy, PZT, magneto-, electro-rheological (MR, ER), high-performance material such as high tensile and ductility concrete, self-repairing material etc. are proposed and performance evaluation method will be proposed.

To conduct the target issues, three sub-committees; System chaired by Prof. A.Wada, Tokyo Institute of Technology, Sensor chaired by Prof. Y.Kitagawa Hiroshima Univ., Effector chaired by Prof. T.Fujita, corresponding to each R/D issues, and one technical coordinating committee (chaired by Prof. S.Otani Tokyo Univ.) are organized. Research organization is illustrated in Fig.1. Building Contractors Association, Housing and Urban Development Cooperation, Building Center of Japan and many materials and sensors makers collaborate the R/D project.

3. ACTIVITIES OF EACH SUB-COMMITTEE

(3-1) Sub-Committee on smart structures system concept

(1) Research Purpose

The objective of this sub-committee is to establish the basic concept and strategies for the development of smart structure system. The followings are the main topics which are discussed in this sub-committee:

1. Definition and categorization of smart structure system
2. Summary of the required performance of smart materials or devices to realize the smart structural system
3. Performance verification of proposed smart structure system concept by computer simulations and experiments
4. Establishment of guideline for the performance evaluation of smart structural system

(2) Research Plan

This sub-committee consists of the following three research working groups:

1. Auto-Adaptive Structural System WG

The objective of this WG is to develop a smart structural system with auto-adoptive features to external disturbance. The research plans are enumerated as follows:

① Propose smart structure system concept with auto-adoptive features

② Examine smart materials or devices to achieve target performance of structure system

③ Verify the proposed structure system concept by computer simulations and experimental tests

④ Establish performance evaluation guideline for the structure system with auto-adoptive features

2. High Performance Structural System WG

The objective of this WG is to develop a high-performance structural system with damage control features or robustness under external disturbance. The research plans are enumerated as follows:

① Propose high-performance structure system concept with damage control features or robustness under external loads

② Examine damage control devices to achieve target performance of structural system

③ Verify the proposed structure system concept by computer simulations and experimental tests

④ Establish performance evaluation guideline for the structure system with damage control features or robustness under external disturbance

3. Smart Seismic Rehabilitation System WG

The objective of this WG is to develop a smart structure system concept for seismic rehabilitation of existing buildings. The research plans are enumerated as follows:

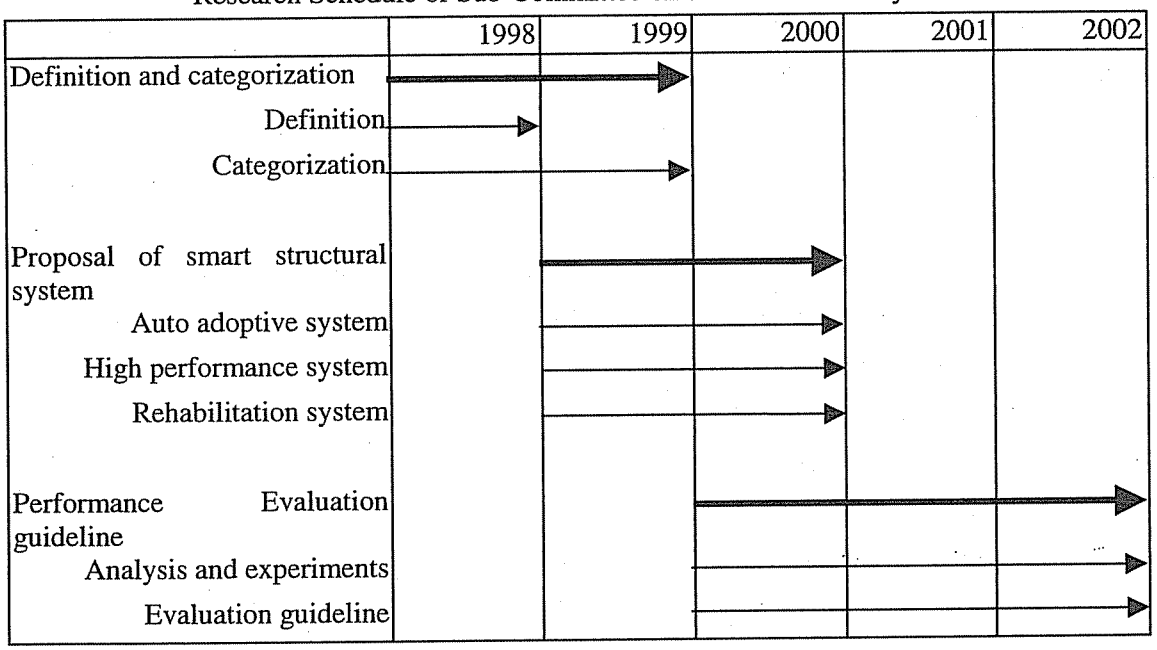
①Survey of seismic performance of existing buildings

②Propose smart structure system concept for seismic rehabilitation of existing buildings

③Verify the proposed structure system concept by computer simulations and experimental tests

④Establish usage guideline for the structure system for seismic rehabilitation of existing buildings

Research Schedule of Sub-Committee on smart structures system



(3-2) Sub-committee of sensing & monitoring

(1) Research Purpose

Sensing & monitoring technology and damage identification methods are treated in this sub-committee. The followings are the main targets of research and development which are discussed in this sub-committee:

1. Structural health monitoring system
2. Structural performance evaluation system
3. Information system with sensors

(2) Research Plan

1. Structural health monitoring system

In this system, the identification methods for detecting structural damages such as yielding, cracks, etc. with some sensors are developed. At first, the technologies for clarifying

whether there are damages or not are developed. Finally these for clarifying the kind and the degree of damage are developed. The followings are main technology and method used for the development.

① Damage identification methods using microtremor & actuator data

② Detection of damage using ultrasonic technique, optical fiber and so on.

2. Structural performance evaluation system

With this system, structural performance such as safety and serviceability can be predicted. Structural serviceability performance can be easily evaluated using minute displacement and vibration properties. However, it is difficult to evaluate structural safety performance without destruct. Therefore, it is important for this research and development issues to make the clear relation between information which are given nondestructive inspection and safety performance such as strength and deformation capacity.

3. Information system with sensors

In this system, the methods for selecting necessary information from enormous information and technology for on-line transaction with sensors are developed. Here the objective of this system is not only a building but also area. As the result, it is possible to make damage map in a moment, for example, and it leads to making change the infrastructures from physical to intelligent.

(3) Research Schedule

The followings are research schedule each R/D system.

Structural health monitoring system

1998 Feasibility study of damage identification

1999 Detection whether there is damage or not

2000 Detection of the part of damage

2001 Detection of the kind of damage

2002 Detection of the degree of damage

Structural performance evaluation system

1998-1999 Arrangement about relation structural Safety to structural performance

2000 Examination analytically

2001 Verification through the implementation example

2002 Final report about Safety performance evaluation

Information system with sensors

1998 Examination about the necessity and the way of using of network

1999-2000 Examination about the necessary technique and the building of a network

2001 Verification through the implementation example

2002 Proposal of a network system

(3-3) Sub-Committee of Effectors

(1) Research Purpose

The main goal of this Sub-Committee is to develop smart structural members which have:

1. embedded smart function(s) such as processors, sensors and/or actuators
2. improved performance (strength, ductility, usability, cost etc.)

(2) Research Schedule

This cooperative research will be held for five years from 1998 to 2002 (Japan side, Fiscal Year). Table 1 shows a typical schedule of development for example. Former three years will be spent to develop smart structural members and the rest two years we plan to perform in-situ, large scale experiment for smart structures with most possible smart materials.

Table 1 Research Schedule

FY		Research Items
1998	-	Basic research for material properties and applications
1999 - 2000	-	Element Test
	-	Development of constitutive model
	-	Analytical study
2001 - 2002	-	Assemblage test
	-	Utilization guidelines

(3) RESEARCH THEMES

Four working groups have been organized to discuss about both practical applications (short term) and future visions (long term) of structural elements with smart materials.

1. Shape Memory Alloys WG
2. Engineered Cementitious Composites WG
3. Electrorheological/Magnetorheological Fluids WG
4. Induced Strain Actuators WG

Possibly we may set additional WGs for other smart materials if their properties were worth to be applied to the building structures.

(3-3-1) Shape Memory Alloys WG

(1) Purpose:

Shape Memory Alloy(SMA) shows three different characteristics depending on the temperature; shape memory effect, pseudo elasticity and these transitional characteristic. 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 smart devices will be developed for these purposes, and the guidelines on SMA for structural design will also be discussed.

(2) Research items and schedule

The research items are planned and scheduled as follows:

1. Survey on current application of SMA to building structures (in 1998)
2. Survey on mechanical properties of SMA for usage of building structural members (in 1998-1999)
3. Development of smart structural members using SMA

3.1) development of SMA devices(in 1999-2000)

3.2) evaluation method of performance of devices(in 2000-2001)

4) Design guidelines for usage of SMA for structural designers

4.1) chapter 1 ; description on mechanical properties of SMA(in 1999)

4.2) chapter 2 ; some application of SMA to structural members(in 2002)

(3-3-2) Engineered Cementitious Composites WG

(1) Purpose

Engineered Cementitious Composites (ECC) is chopped fiber reinforced mortar/concrete microstructurally designed using micro-mechanical principles. ECC exhibits strain-hardening with superior strain capacity, shear ductility, and extreme damage tolerant mechanical behavior.

The purpose of this research is to develop high performance cementitious structural elements as energy dissipation devices and damage tolerant elements utilizing Engineered Cementitious Composites (ECC) to achieve a smart damage tolerant structural system. A Concrete-encased steel column without reinforcing bar, which is a new type steel-concrete composite using high performance bonding agent and ECC, will also be developed as an example of application of ECC. Applications to both new structures and in retrofitting of existing R/C structures to withstand future earthquakes are considered.

(2) Benefits

ECC devices and ECC elements are expected to decrease the response and damage of building structures under external disturbances to realize 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.

Stiffness, strength and ductility of the ECC devices can be controlled easily by it's dimensions and types of ECC materials used. Since the ECC device 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. Then the column members can hold the vertical load without any damage by the expected horizontal deflection.

The damage tolerant elements can be achieved by the extreme damage tolerant mechanical behavior of ECC. Since crack width of ECC elements can be easily controlled less than 0.3 mm even in the large deformation state, high level of reparability, serviceability and durability can be added to the buildings.

(3) Research Items

1. Development and clarification of properties of ECC materials
2. Development of ECC devices by experimental and analytical

investigations

3. Development of damage tolerant elements
4. Design guideline for smart structural system with ECC devices and elements
5. Development of concrete-encased steel column elements without reinforcing bar

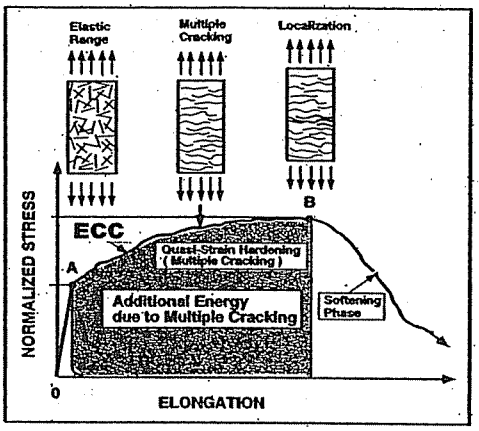


Fig.1 Uniaxial tensile stress-strain relationship of ECC

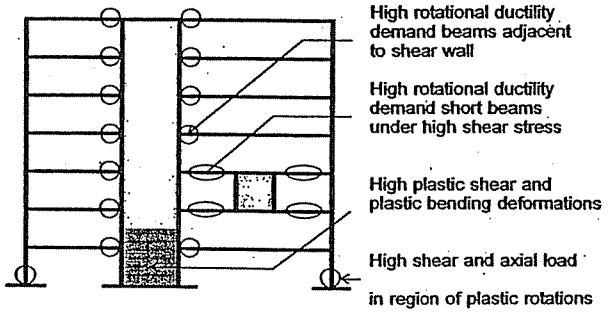


Fig. 2 Typical examples of selective use of ECC elements in seismic resistant structures

3.3 Electro/Magneto Rheological Fluids WG

(1) Purpose:

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 variable contenders for development controllable devices.

The purpose of this issue, is to develop an adaptive structure that controls its stiffness and damping characteristic to behave adaptively against earthquake or wind forces and obtain safety and function by using ER/MR devices with lesser energy (Figures 3-5). For the purpose, ER/MR devices and control algorithms are developed and their validity are discussed by analytical study and shaking table test.

(2) Research Items

1. Clarification of characteristics of ER/MR fluids
   - Viscous characteristic and achievable yield stress
   - Transition time and electric and magnetic intensity to become semisolid
   - Influence of outside, for example, temperature, etc.
2. Development of ER/MR devices
   - Damping coefficient obtained by the device
   - Capacity to fix the structural member, for example braces
3. Development of control algorithm
   - Adaptive control of the structure to obtain the safety and function against earthquake and wind forces
   - Saving energy

- Sensing system

4. Analytical study and shaking table test
   - Verification of the validity of the algorithm and devices

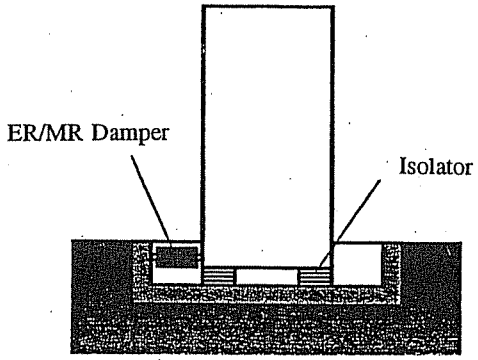


Fig. 3 Base Isolated System Controlled by Variable Damper

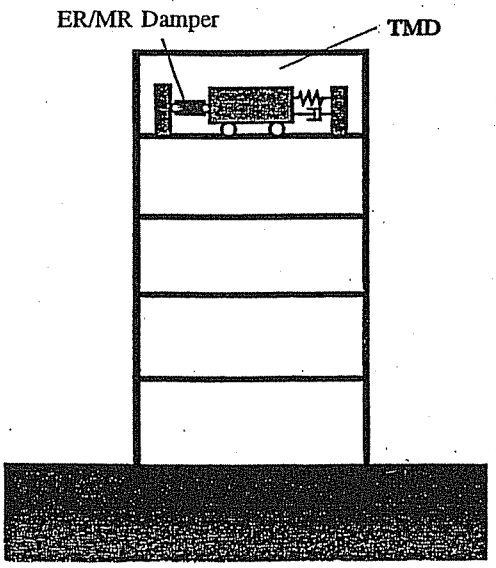


Fig. 4 Tuned Mass Damping System Controlled by Variable Damper

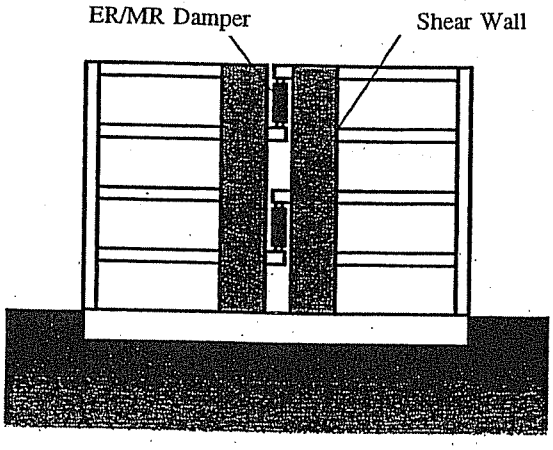


Fig.5 Semi-Active System Controlling Stiffness

(3-4) Induced Strain Actuators WG

(1) Purpose

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.

(2) Research Items

(a) controlling members

ISA materials are very suitable for structural control. In addition, polymer based ISA films or distributed ISA devices can control vibration mode of plane members. We try to integrate ISA materials into normal structural members such as columns, beams, walls etc.

to realize smart structural systems. See Figs. 6-8.

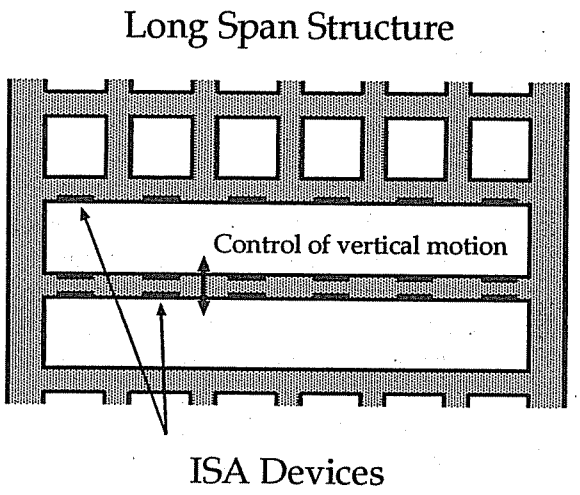


Fig. 6 Long Span Structure

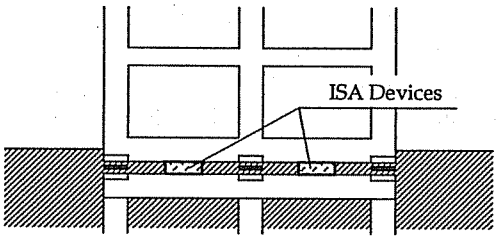


Fig. 7 Axial Force and Friction Control (for Base Isolator. Including trigger application)

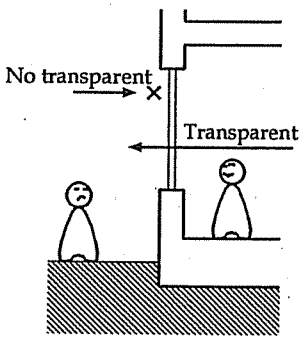


Fig. 8 Active Sound Transparency

(b) Sensing members

ISA materials can act as sensors because they cause change of electric or magnetic fields under deformation. Wireless application is also discussed.

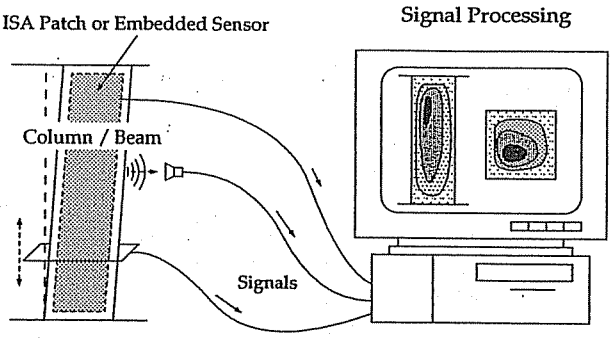


Fig. 9 Sensing with or without Cabling

4.CONCLUSIONS

This development research aims to apply the new technology like new materials and new structural systems, to develop smart structure systems which makes the performance of buildings advanced, to reduce the expense of construction and maintenance and eventually to ensure the future sustainability without trouble. Building Research Institute, Ministry of Construction (BRI) and National Science Foundation, U.S.A. has started the research and development of " Smart Structure Systems " in 1998. Feasibility study of smart structure system be developed are introduced.