SMART STRUCTURAL SYSTEMS FOR EXPOSED TO EXTERNAL DISTURBANCES - CONCEPT AND TECHNOLOGY

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SUMMARY

Construction of control systems for buildings structures is difficult due to many unknown variables, such as the structure type, material, site condition, and the temporal deterioration of the structural performance. These problems can be overcome by developing smart structural systems. A smart structural system is not merely a control system that adds intelligent functions, but also functions as a sensor, date processor, actuator, and expression for external disturbances. Incorporating genetic algorithms into response-control systems will make the self-organization of control systems and their organic optimization economically feasible in the near future.

Characteristics of fuzzy-theory algorithms can be merged with genetic algorithms by selecting or

improving the rules of fuzzy theory. Consequently, introducing smart structural systems into buildings is practical only when coupled with the development of smart materials, such as piezoelectric and glass fiber materials. Structural interpretation of the aspects of artificial life will coincide with the development of technology related to each aspect.

In this paper, we first review the classification and characteristics of structural response-control systems. We then summarize the classifications of the control principles, and the required performance characteristics of control systems. To demonstrate how the fundamental performance of piezoelectric materials can be incorporated into smart material systems, we made vibration tests of scaled cantilevered beam and portal frame. The results of vibration tests confirmed the validity of the control effect of the response-control system and demonstrated the possibility of classifying the fundamental performance of piezoelectric materials when used as actuators, sensors, and dampers. Finally we speculate on the general concept and the prospects of using smart material systems in active-response control systems.

INTRODUCTION

Japan is subjected to frequent seismic activity due to its location within three major earthquake zones : the Pacific Ocean side, which produces large earthquakes; the Japan Sea side, which produces medium-sized earthquakes, and the inland areas, which produces shallow, medium-sized earthquakes. Protection against earthquakes is therefore required in building construction. In addition to designing buildings with proper structural resistance, it is also important to maintain the safety and functionality of buildings, as well as the living comfort of the residents during earthquakes and strong winds. Designing a building to be a response-control structure is the most effective way to economically meet this societal demands.

For building structures, it is generally difficult to construct control systems because there are many unknow

variables such as the type of structure, material, site condition, and the temporal change of the structural performance. For controlling the structural vibrations during earthquakes, the response time of the control

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system must be sufficiently short to minimize the time between sensing an external turbulence and operating the actuators of a control system. It is difficult, however, to design control algorithms that can handle arbitrary scenarios for controlling large, complicated response-control systems, which are necessary for buildings that are built in unpredictable environment. As the complexity of the control systems increases, the possibility of providing accurate, comprehensive information decreases, thus degrading the responsiveness, reliability, safety and robustness of the system. To overcome these problems, the development of active-response control systems is needed.

In this paper, we present the conceptual design for an active-response control system that uses smart materials. We first review the classification and characteristics of structural response-control systems. We then summarize the control principles for these systems, and their required performance. We then describe how the innate performance of piezoelectric materials, which we call a smart material, can be used to make actuators sensors and dampers. We then describe vibration tests and results for evaluating the performance of scaled cantilevered beam and portal frame that use smart materials. Finally, we speculate on the general concept and the prospect of using smart materials and related systems.

CLASSIFICATION AND CHARACTERISTICS OF RESPONSE-CONTROL STRUCTURES

Response-control structures can be classified according to whether or not they require energy input to restrain and control the response of building to external disturbances. Active systems require energy to directly resist the external disturbances, semi-active systems require energy to indirectly resist external disturbances by changing the dynamic characteristics of the building structure, and passive systems do not require any energy input. Passive systems include base-isolation and the Tuned Mass Damper (TMD) systems. Hybrid systems are a combination of active and passive systems, supplying energy to enhance the damping effect of the passive system.

Of these response-control structures, active systems provide various countermeasures by using the external disturbance signals generated by sensors installed either inside or outside the building. Active systems use either feedforward control, in which sensors outside the building detect disturbance before it reaches the building, and feedback control, in which sensors in the building detect the building's response[1]. When buildings are subjected to dynamic forces, the resultant motion can be represented as:

$$m\ddot{x} + c\dot{x} + kx = f + p \tag{1}$$

where ***m*** is the mass of the vibration system, ***c*** is the viscous damping coefficient, ***k*** is the stiffness coefficient of the vibrating system, ***f*** is the external force acting on the vibration system, ***p*** is the response control force, $\ddot{x}$, $\dot{x}$, and x are the response acceleration, velocity, and displacement, respectively, with respect to the ground. Each term in Eq. (1) is expressed in either matrix or vector form. Restriction or control of the building's response to external disturbances is measured by, $\ddot{x}$, $\dot{x}$ and x. The object of a response-control structure is to reduce these factors by controlling or adjusting ***m***, ***c***, ***k***, ***f***, or ***p***. According to these basic principles of dynamics, the available structural response-control methods can be classified as follows:

(1) Methods based on the control and adjustment of ***m***, such as rigid- or liquid- mass dampers.
(2) Methods based on the control and adjustment of ***c***, such as variable damping mechanisms and building-to-building connection mechanisms.
(3) Methods based on control and adjustment of ***k***, such as variable-stiffness and flexible-base mechanisms.
(4) Methods based on the control and adjustment of ***p***, such as using reaction walls, jet or injection devices.

The structural response-control concepts in theory differ from conventional systems for earthquake or wind-resistant structures in their method of introducing the controlling force. In conventional systems the control force is applied to columns, girders, walls, and braces as restoring force characteristics or energy absorption, where as in response-control systems the control force is applied to the mechanical equipment.

CONTROL PRINCIPLES AND REQUIRED PERFORMANCE OF CONTROL SYSTEMS

Currently, the most commonly used response-control method in structures is feedback control, which feeds back $\ddot{x}$, $\dot{x}$, and x to the control system. Classical control principles are used to obtain vibration control at the design stage of the control system, such as shifting the natural frequency of the structure of the predominant frequency of the external disturbance or increasing the damping factor. On the other hand, modern control principles are used to feed back information to the control system with controllability and sensing ability. However, if these problems are solved, the dynamic characteristics of the control system can be easily changed. Control principles may be classified into the following four groups:

(1) Self-organizing structural control, in which the optimum configuration of a control system is determined by the control system itself.
(2) Adaptive control, in which an evaluation function and the parameters to be optimized are determined adaptively in a given structure.
(3) Optimum control, in which the operational quantities, such as the response parameters of Eq.(1), are determined so as to optimize a given evaluation function.
(4) Direct control, in which the operational quantities are directly determined by matching the process variables with their target values.

These classifications are based on two factors: the degree of complexity of the system and the degree of uncertainty in the information. In the design of a structural response-control system, it is important to identify the dynamic characteristics of the structure that are to be controlled. It is also necessary to include fail-safe mechanisms to improve the reliability of the entire system . Therefore, it is desirable to develop fail-safe systems that have adaptive control, in which the control parameters can be adjusted in response to environmental effects.

In building structures, it is generally difficult to construct control systems because of the large number of unknown variables such as the type of structure, materials, and site conditions, and the temporal rate of deterioration of structural performance. To control the vibration of a structure subjected to earthquakes, a fast response time of the control system is critical. The response sequence includes sensing the external disturbance, conveying the signal to the control circuit, and putting the actuators into operation. There are, however, many uncertainties in the input signals to a control system, such as the direction of the input ground motion and location of the sensors.

To deal with these uncertainties, optimum control systems that incorporate fuzzy logic or neural networks must be used. Figure 1 shows an example of the relationship between response-control system requirements and control principles for structural safety evaluation of a response-control structure, and Fig. 2 shows a flowchart of a control system that uses fuzzy optimal control, as an example[2]. This system uses fuzzy theory to make real-time predictions of earthquake ground motion and to obtain the response function from a combination of real-time structural identification, a target response that satisfies the living comfort and safety of the residents, and target control variables determined for economy and technology. From this information, the fuzzy control method determines the optimum response.

VIBRATION TESTS ON PIEZOELECTRICTRIC MATERIALS

To develop a comprehensive smart material systems, it is necessary to focus on either the innate characteristics of material itself or on a combination of computational and mechanical technology that combines a sensors, actuators, data processing, and expression. As a controllable materials in a smart material systems, piezoelectric, magneto-strictive, magneto-rheological(MR), electro-rheological(ER), and shape-memory alloys(SMA) materials, which have been tried to use in Aeronautical Engineering, are considered to develop the optimum applications in controlling large-sized and complicated building structures. To demonstrate how the innate performance of piezoelectric materials can be incorporated into a smart material systems, we made vibration tests of cantilevered beam and of a portal frame.

Vibration Tests

To demonstrate the applicability of piezoceramic materials for sensing, actuating and damping, we made three types of vibration tests. Figure 3 shows the cantilevered beam we used, Figs. 4(a) and (b) show the sensing and actuating systems, respectively. A bimorph, consisting of a steel plate and two piezoceramics plates, was installed in the fixed end of the beam. Figure 5 shows detail of the bimorph used for the vibration tests. The material and electrical properties of the piezoceramic are shown in Table 1. The portal frame and the system used for the damping verification tests are shown in Figs. 6 and 7, respectively. Bimorph similar to that installed in the beam where installed in the end of the portal frame columns. For the bimorphs installed in the portal frame columns, however, an adjustable resistor was used to shunt the piezoceramic electrodes. In all tests, the strain , ε, was measured in the vicinity of the fixed end. Also, in the sensing verification tests, the strain of the piezoceramic sensors in the bimorph, ε_c, was also measured. The output from the piezoceramic sensors was calibrated by using the amplitude of strain measured in a vibration tests with a beam vibrating at its natural frequency, *f*, of 6.0Hz.

In all of the tests the excitation was done with a shaking table. For the sensing verification tests the excitation forms were sinusoidal excitation with , *f*, of 6.0Hz, and 11.0Hz, and for the actuating and damping verification tests, excitation was four sinusoidal cycles at the system's natural frequency, *f*, of 6.0Hz and 12.8Hz. In actuating verification tests, an AC voltage of 250V, and an inverse phase of 6.09Hz was applied to the piezoelectric materials.

The damping ratio, *h*, in each test was calculated from vibration data measured for free vibrations, by using a least-square method based on the following equation:

$$|\varepsilon_a| = a \cdot \exp\left\{-h \cdot \frac{2\pi}{T_1} \cdot t\right\} \tag{2}$$

where $|\varepsilon_a|$ is the strain amplitude, ***t*** is time, ***a*** is the amplitude at ***t=0***, and T_1 is the natural period.

Optimum Resistor in Piezoceramic Damper

Under the steady-state vibrations, the equivalent damping ratio added by the piezoceramic damper, $\boldsymbol{h_{add}}$, is obtained as follows [3,4]:

$$h_{add} = \frac{\eta}{2} \cdot \frac{U_p}{U} \tag{3}$$

Where;

$$\eta(f) = \frac{\rho \cdot k_{31}^2}{\left(1 - k_{31}^2\right) + \rho^2} \tag{4a}$$

$$\rho = R \cdot C\left(1 - k_{31}^2\right) \cdot 2\pi \cdot f \tag{4b}$$

η : Loss factor, ρ : Non-dimensional frequency ,
U_p, U : Peak strain energy in the piezoelectric materials and the total system,
k_{31} : Electromechanical coupling coefficient (3: Polling direction and 1: Vibration direction),
R : Resistance (Ω), C : Static capacitance (F), f : Frequency of excitation

The optimum resistance, R_{opt}, that maximizes h_{add} can be determined as:

$$\frac{\partial h_{add}}{\partial R} = 0 \tag{5}$$

Consequently,

$$R_{opt}(f) = \frac{1}{C\sqrt{1 - k_{31}^2} \cdot 2\pi \cdot f} \tag{6}$$

Results and Discussions

Figures 8(a) and (b) show results for sensing tests, Figs. 9(a) and (b) show results for actuating tests, and Figs. 10(a) and (b) show results for damping tests. The temporal strain response of the piezoelectric materials are shown in Fig. 8(a) for *f*=6.0 Hz and in Fig. 8(b) for *f*=11.0 Hz. Figures 9(a) and (b) show the temporal vibration of strain in the vicinity of the fixed end with and without actuation, respectively. In Fig. 9, ε is normalized by the strain measured when the top of displacement of the specimen reaches 1.0 cm, $\varepsilon / \varepsilon_a^*$, and *t* is normalized by the natural period, t/T_1 . Figure 10 shows R/R_{opt} vs. *h*, in which R_{opt} is calculated from Eq.(6) and *h* is calculated from Eq.(2). The results shown in Fig. 10(a) correspond to R/R_{opt} was varied from 0 to 10 and the results shown in Fig. 10(b) correspond to R/R_{opt} varied from 0 to 2. In Figs. 10(a) and (b), the relationship between R/R_{opt} and $h_{add} + h_{inh}$ calculated from Eq.(3) are also plotted. Where, the inherit damping ratio, h_{inh}, is identified as the experimental observation when the resistance is to be 110 (kΩ).

From these results, we clarified that:

1) The amplitude and phase of strain measured with the piezoceramic sensor depended on the frequency of excitation.
2) The piezoceramic actuator was able to control the vibration at 1.5 times its inherit damping ratio.

3) The optimum resistance of the piezoceramic damper that maximized the damping ratio was accurately predicted by Eq.(6).
4) When the damping was attached over only 10% of the column, the piezoceramic damper increased the damping ratio by 30% compared with its inherit damping ratio.

PROSPECTS FOR SMART MATERIAL SYSTEMS

A smart material is one that not only adds intelligent function, but one that also functions as a sensor, data processor, actuator, and expression for external disturbances. That is, smart materials add an aspect of artificial life. This is different from intelligent materials, which only respond according to a single set of input-output (non-evolving) response characteristics. Recently many research studies are being made on artificial life, focusing on evolution, shape-formation, learning, distributed parallel biological processing, immunity, and self-remodeling [5,6]. As one of the basic mathematical functions of artificial life, genetic algorithms based on the principle of biological evolution (i.e., selection, crossover, and mutation) are the models for the evolution process. Among the possible processing functions, evolution is the most useful method for optimization, because the system responds according to simple internal principles and through interactions with outside sensors, and not by external instructions. Thus, self-organization can independently form the system order. Also, self-formation is the mapping from a genetic type to an expressing type, and has the important role of enhancing the robustness of the system adaptability.

In designing and controlling large-sized, complicated response-control systems (necessary for buildings that are in uncertain and changing environments), it is impossible to provide control algorithms and data that can handle every control scenario. As the complexity of the control system increases, the possibility of providing accurate, comprehensive information decreases, thus degrading the responsiveness, reliability, safety, and robustness of the system. To avoid this, the development of smart material systems that use them is needed. Figure 11 shows the overview of smart material systems that use them , as modification to reference [7].

Figure 12 shows the technical development of building structures from the late 20th century to the first half of 21st century. Currently, earthquake disaster countermeasures for buildings are seismic design and response-control devices, such as actuators and sensors. Monitoring is also a must for maintaining and controlling such response-control devices. In the future, incorporating genetic algorithms into response-control systems will make the self-organization of systems and their organic optimization economically possible (i.e., economization). Fuzzy theory and neural networks are examples of artificial intelligence. It is possible to merge the characteristics of each of these algorithms by adopting genetic algorithms for selecting or improving the rules of fuzzy theory or neural networks. Consequently, introducing smart material systems into buildings is practicable only when coupled with the development of smart materials. Structural interpretation of the aspects of artificial life (i.e., evaluation, shape formation, learning, distributed parallel processing, immunity, and self-remodeling) will coincide with the development of technology related to each aspect. Incorporating smart material systems into buildings (i.e., smartization) is the future of earthquake countermeasures; the ultimate goal of engineers is to design buildings that behave like a human being.

CONCLUDING REMARKS

In this paper, we reviewed the classification and characteristics of structural response-control systems, and presented the advantages of active response-control systems. We then looked at the classifications of the control principles behind three systems, and also reviewed the required performance of control systems. To demonstrate how piezoelectric materials can be incorporated into smart material systems, we made vibration tests with scaled cantilevered beam and portal frame.
The results of vibration tests confirmed the validity of the control effect of the response-control systems and demonstrated the possibility to clarify the characteristics and performance of piezoelectric materials for use as actuators, sensors, and dampers in a smart material systems. Finally we speculated on the general concept and the prospects of using smart material systems in future building designs.

The performance of structural response-control systems depends on the control devices, which have been developed mainly from a practical-use viewpoint. When we reach a consensus on the requirements of future structural control systems, incorporation of smart materials into these systems will proceed. When that occurs, it will be important to develop reliable smart material technology and methods for evaluating the vulnerability of each component of structural response-control systems.

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Table 1 Mechanical and electrical properties of piezoceramic used in bimorph

Lead Zirconate Titanate Ceramics ($PbZrO_3$-$PbTiO_3$)		
Young's Modulus	E_{11}	5.8×10^{10} (N/m^2)
Poisson's Ratio	ν	0.35
Relative Dielectric Constant χ_0=8.854×10^{-12} (F/m)	χ_{33}/χ_0	2000
Piezoelectric Constant	d_{31}	195×10^{-12} (m/V)
Electro-mechanical Coupling Coefficient	k_{31}	0.35
Static Capacitance (Bimorph + Piezoceramic)	C	120(nF) , (24×30nF)

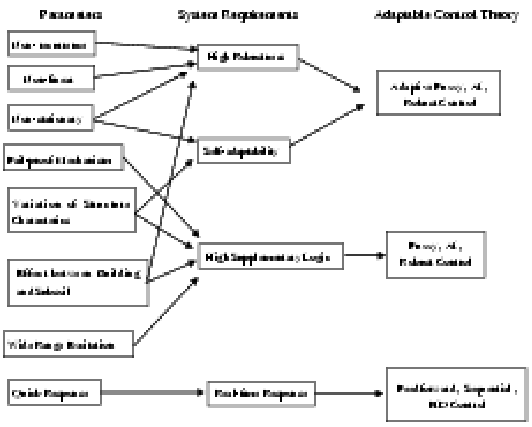

Figure 1 Relationship between adaptive control theory and response-control system requirements

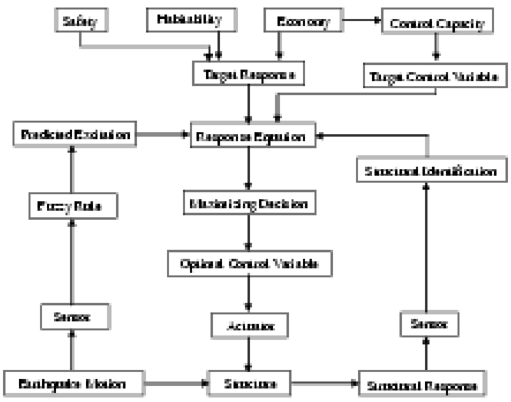

Figure 2 Flowchart of a fuzzy optimal control system[2)]

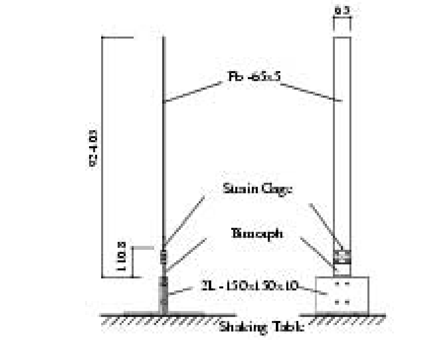

Figure 3 Cantilevered beam specimen (Type A specimen)

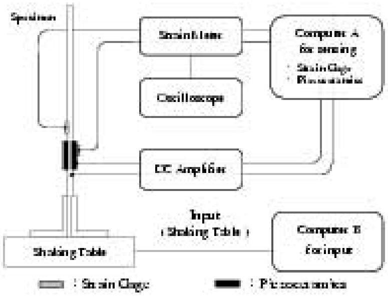

Figure 4(a) System for evaluating sensing function

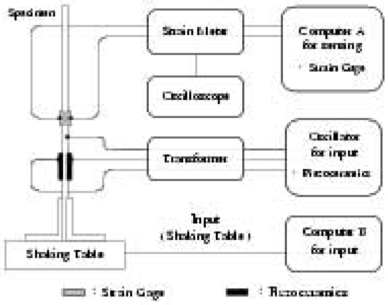

Figure 4(b) System for evaluating actuating function

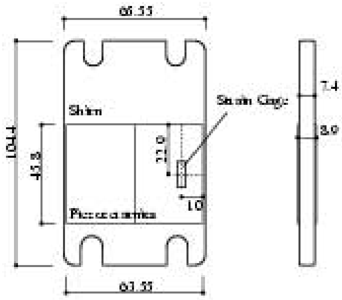

Figure 5 Detail of bimorph

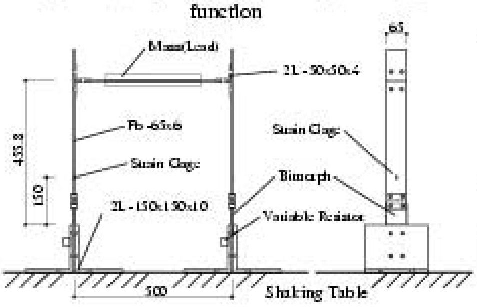

Figure 6 Portal frame specimen (Type B specimen)

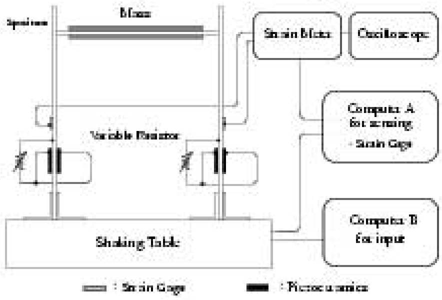

Figure 7 System for evaluating damping function

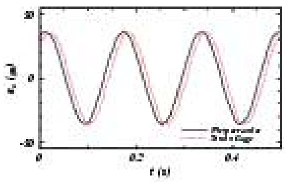

Figure 8(a) Strain indicated by piezoceramic sensor compared with strain indicated by strain gage (f=**6.0Hz**)

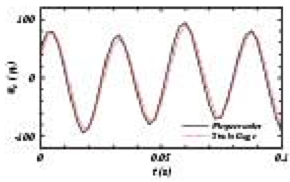

Figure 8(b) Strain indicated by piezoceramic sensor compared with strain indicated by strain gage (f=**11.0Hz**)

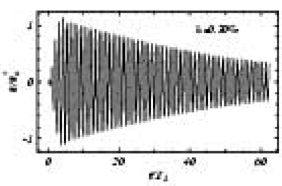

Figure 9(a) Time history of strain response of type A specimen with piezoceramic actuator

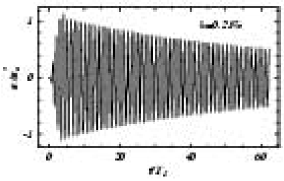

Figure 9(b) Time history of strain response of type A specimen without piezoceramic actuator

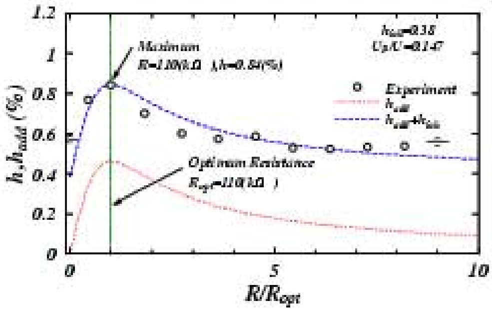

Figure 10(a) Measured and calculated damping ratios for R/R_{opt} varied from 0.0 to 10

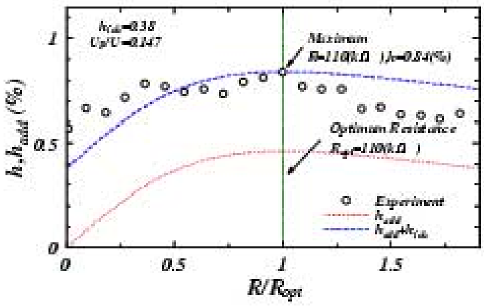

Figure 10(b) Measured and calculated damping ratios for R/R_{opt} varied from 0.0 to 2.0

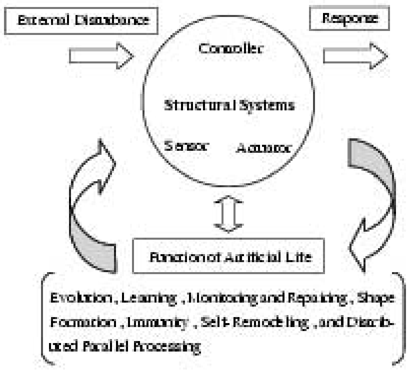

Figure 11 Overview of smart material systems(added to 7)

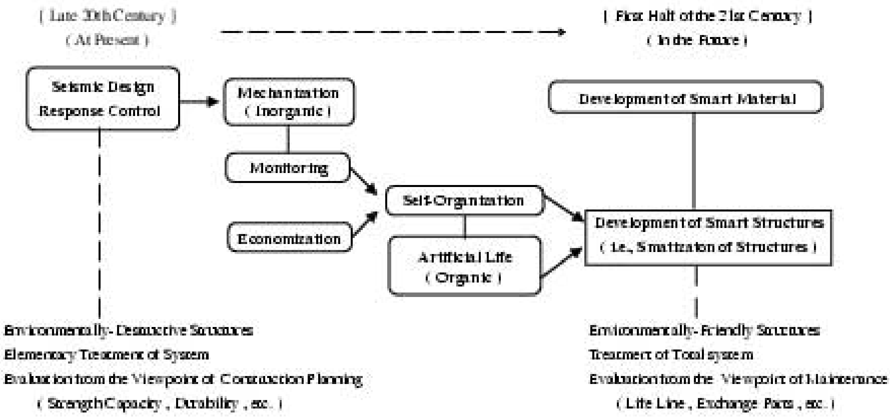

Figure 12 Post and future technical development of building construction