RESEARCH AND DEVELOPMENT OF SMART STRUCTURAL SYSTEMS

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SUMMARY

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. U.S. Counterpart is National Science Foundation. Smart Structural Systems (also called as Auto-adaptive Media) are defined as systems that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life. The research and development of (1) Concept and performance evaluation method of smart structure system, (2) Sensing of structure performance, and (3) Development and evaluation of structural elements using smart materials will be conducted.

INTRODUCTION

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

Smart Structural Systems are defined as structural systems with a certain-level of autonomy relying on the embedded functions of sensors, actuators and processors, that can automatically adjust structural characteristics, in response to the change in external disturbance and environments, toward structural safety and serviceability as well as the elongation of structural service life[Otani 1999].

TARGET ISSUES AND RESEARCH ORGANAIZATION

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

1. Concept and performance evaluation: A series of auto-adaptive and high-performance systems are developed, and methods of performance evaluation are investigated.

2. Sensing of structure performance: Damage detection methods utilizing smart materials as sensors, such as Optical Fiber, Carbon Fiber, Shape Memory Alloy (SMA), and a Piezoelectric Ceramic (PZT) in addition to existing sensors are investigated, and methods for system identification associated with damage detection are studied.

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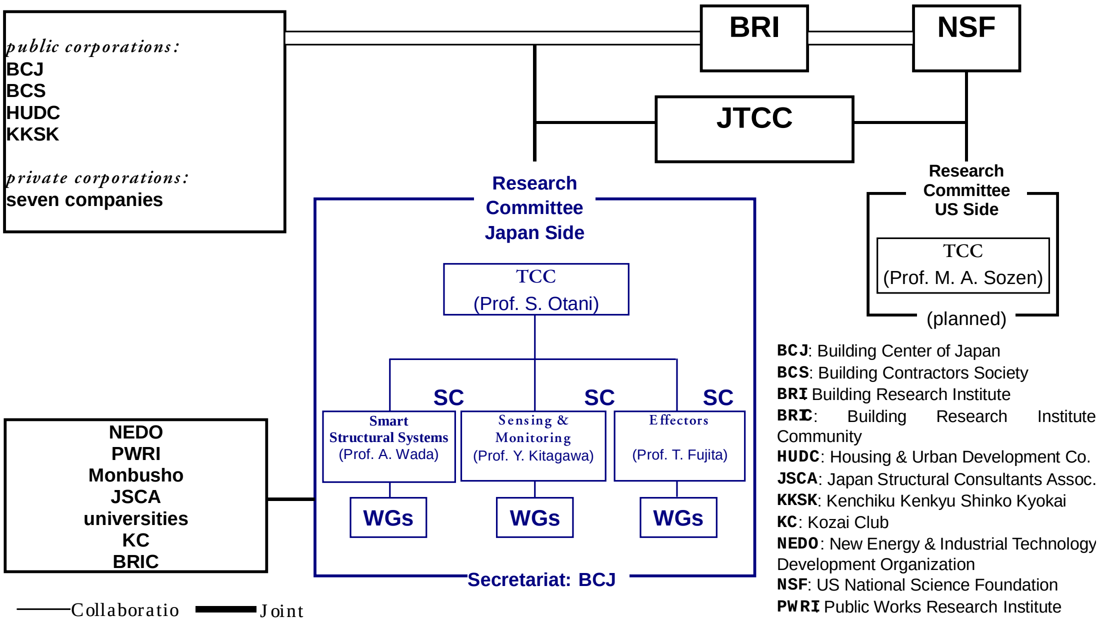
3. Development and evaluation of smart structural elements: Devices utilizing the auto-adaptive material such as SMA, PZT, Magneto-Rheological (MR) and Electro-Rheological (ER) Fluids, high tensile strength and ductility concrete, self-repairing material are developed.

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

- "Sub-committee on structural system" chaired by Prof. A. Wada of Tokyo Institute of Technology,
- "Sub-committee on sensing and monitoring technology" chaired by Prof. Y. Kitagawa of Hiroshima University,
- "Sub-committee on effector technology" chaired by Prof. T. Fujita of Institute of Industrial Science, University of Tokyo.

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



CONCEPT OF SMART STRUCTURAL SYSTEMS FOR BUILDINGS

The concept of smart structural system was initially proposed in the field of aerospace engineering, where the smart structural system was defined as "a system that can detect damage, restrain damage propagation, control the response from external disturbances actively, and adapt its configuration to optimum state for the environment." The objectives and needs of a smart structural system for building engineering are different from those for aerospace engineering as shown in Table 1; i.e., the value of a building should be determined not only by structural safety but also taking into account non-engineering points of view such as "beauty", "economy", and "function". Environment around a building and environment itself are also important in building engineering (see Figure 2). Table 2 summarizes the research needs of a smart structural system for buildings.

Table 1 Smart Structural System for Aerospace Engineering and Building Engineering

	Aerospace Engineering	Building Engineering
Design Philosophy	Integrate smart functions into a structure to achieve light-weight and high-performance.	Put smart functions to a structure to achieve objective performance at minimum life cycle cost.
Characteristics of structure	Airplane is originally active and adaptive. Airplane has a simple usage and works as a single unit.	Building is not required to be active or adaptive. 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. Constant maintenance is required.	Structure must be safe in rare events, such as strong winds or an earthquake. Free-maintenance is desirable.
Research needs	Development of smart devices integrated into a structure.	Development of a system effective for objective performance. High demand for health monitoring.

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

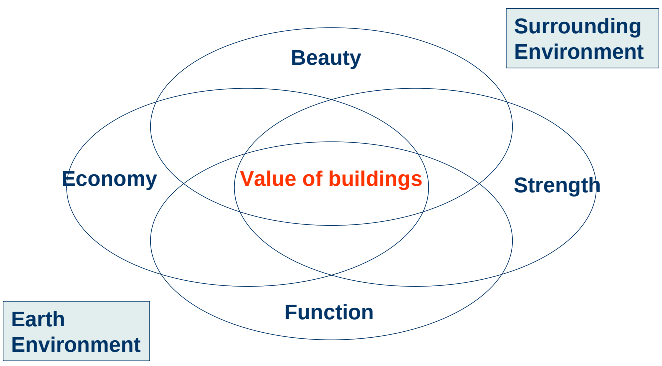


Figure 2 Evaluation Elements of Building

SENSING AND MONITORING TECHNOLOGY

Sensing and monitoring are key features of smart structural systems, and the followings are the main targets of research and development:

1. Structural Health Monitoring
   Methods to detect structural damage[Los Alamos National Laboratory 1996] such as yielding of metal and cracking of materials, using sensors need to be developed with an emphasis on the followings items;
   - Damage identification methods using micro-tremor response and actuator data.
   - Damage detection methods using ultrasonic technique and Optical Fiber.

   The images of Structural Health Monitoring are shown Figure.3 - 5.
2. Structural Performance Evaluation
   Evaluation methods for structural performance objectives such as safety and serviceability need to be developed. Structural performance at the serviceability limit state may be evaluated from small displacement response or by the change in vibration characteristics. It is more difficult to evaluate the structural safety without destruction tests. It is desired to use the information from non-destructive inspection to evaluate the safety performance objectives such as strength and deformation capacity.
3. Information System with Sensors
   Methods to select necessary information from enormous sources of information using on-line transaction needs to be developed. In some cases, a group of buildings must be monitored in a selected area.

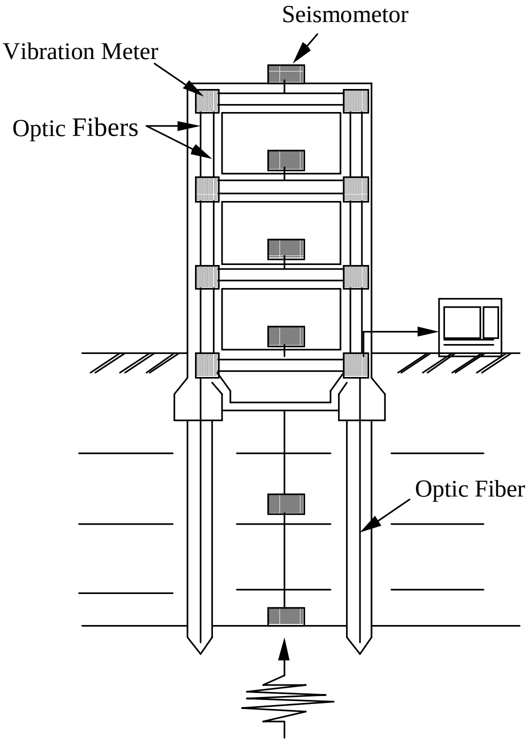


Figure 3 : Set up Health Monitoring

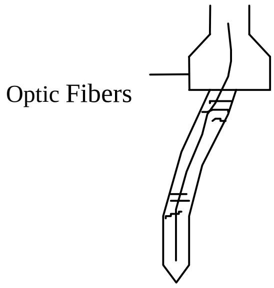


Figure 4 : Damage Detection of Pile using O.F.

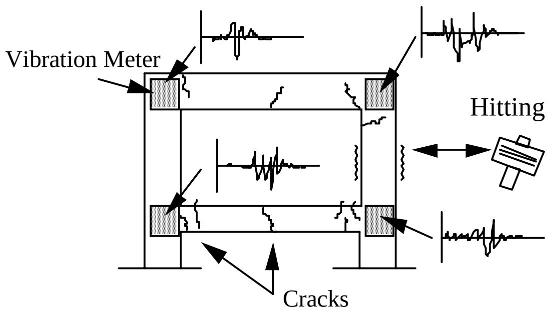


Figure 5 : Damage Detection after Damage

EFFECTOR TECHNOLOGY

Smart materials with embedded desired functions such as sensing and processing or with improved structural performances such as high strength, ductility, usability and low cost are explored and the characteristics of these materials should be investigated. The four smart materials have been selected for study:

1. Shape Memory Alloys
   Shape Memory Alloy (SMA) shows three different characteristics depending on the temperature; shape memory effect, pseudo elasticity and these transitional characteristics. The application of SMA materials in

a smart structural system for buildings is to be studied. It is intended to develop smart devices and guidelines for use of SMA in structural design. The research items for this purpose are as follows:

- Survey on current application of SMA to building structures,
- Survey on mechanical properties of SMA for use in building structural members,
- Development of smart structural members using SMA, and
- Design guidelines for use of SMA in structural designers.

2. Engineered Cementitious Composites

Engineered Cementitious Composites (ECC) is mortar or concrete reinforced by chopped fiber. Such composite materials have been micro-structurally designed using micro-mechanical principles. ECC exhibits strain-hardening with large strain capacity and shear ductility, and good damage tolerant mechanical behavior. It is intended to develop the use of high performance cementitious structural elements as energy dissipation devices and damage tolerant elements to achieve a damage tolerant structural system. The research items include the followings:

- Development and clarification of properties of ECC materials,
- Development of ECC devices by experimental and analytical investigation,
- Development of damage tolerant elements,
- Design guideline for smart structural system using ECC devices and elements, and
- Development of concrete-encased steel column elements without reinforcing bars.

3. Electro/Magneto Rheological Fluids

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 variable contenders for development of controllable devices. It is intended to develop a structure that controls its stiffness and damping characteristic to behave adaptively against earthquake or wind forces and achieve safety and function by using ER/MR devices with lesser energy. The research items include the followings:

- Clarification of characteristics of ER/MR Fluids,
- Development of ER/MR devices,
- Development of control algorithm, and
- Analytical study and shaking table tests to confirm the reliability.

4. Induced Strain Actuators

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 small/precision machines because of some advantages from viewpoint of small sizes, rapid reaction, high power, and high accuracy etc. ISA materials act as sensors because they causes change in electric or magnetic fields under deformation. It is intended to develop smart members to realize smart, comfortable and safe structures. The research items are planned as follows:

- Vibration mode control of structural members using ISA materials, and
- Development of sensors using ISA materials.

Possible application examples are:

- Long Span Structure,
- Axial Force and Friction Control (for Base Isolator, including trigger application),
- Active Sound Transparency (Noise Control) [Ahn 1998], and
- Wireless sensors of deformation

See Figure. 6 and 7.

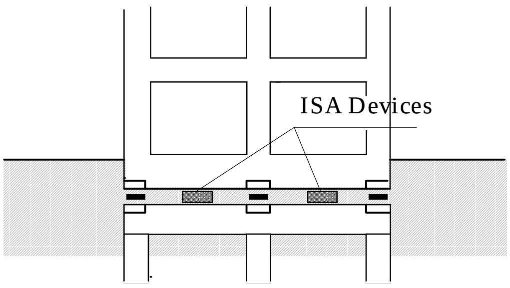


Figure 6 : Axial Force and Friction Control

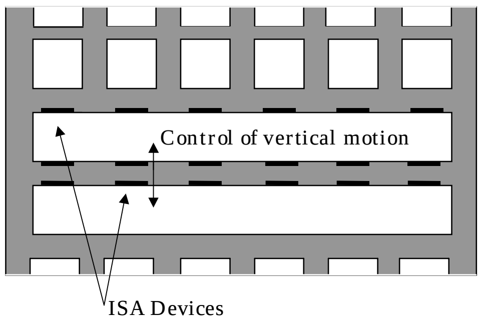


Figure 7 : Active Floor Vibration Control

SURVEY OF SMART STRUCTURAL SYSTEMS IN JAPAN

The current status of research and development of smart structural systems was surveyed in Japan. Questionnaires were sent to a total of 247 Japanese researchers and companies in wide fields of engineering, including material production, mechanical engineering, transportation and construction. These institutions were selected from lists of technical papers and internet web-pages active in smart structure research. The response was received from 68 institutions. Table 3 summarizes the number of answers in each engineering field.

Table 3 Number of Responses to Questionnaires

Institute Field	University	National Institute	Private Company	Total	Ratio(%)
Material	5	2	8	15	26.3
Mechanics	10	0	3	13	17.3
Car/Train/Ship	1	0	11	12	28.6
Aerospace	4	1	1	6	21.4
Construction	7	1	14	22	48.9
TOTAL	27	4	37	68	25.9
Ratio(%)	27.0	15.4	30.6		

The brief summary of the questionnaire is described below:

Q1. Smart Materials
Figure 8 shows a bar chart of the number of systems for each smart material. In the field of construction, many systems use Optical Fibers and Carbon Fiber and Glass Fiber Reinforced Plastic (CFGFRP) for the purpose of health monitoring. On the other hand, in the field of aerospace, Induced Strain Actuator (ISA) materials are mainly used for the purpose of active control.

Q2. Objectives of Using Smart Materials
As shown in the bar chart in Figure 9, the main objective of using smart materials is to improve serviceability and function of the system. In the field of construction, many systems use smart materials to improve safety and durability.

Q3. Basic Functions of the System
The bar chart in Figure 10 shows the number of systems with each of the basic functions; 1) sensing and monitoring, 2) response and control. Most of the systems in the field of construction have functions of sensing and monitoring. On the contrary, most of the systems in other engineering fields have functions of response and control.

Q4. External Disturbances
As shown in the bar chart in Figure 11, in the field of constructions, the main disturbances for the systems are displacement, vibration and deterioration. The frequency of the disturbance is also asked, and it was found that most systems consider the disturbance of usual event. Only a few systems consider the disturbance of rare event such as a large earthquake.

Q5. Stage of Development
Development stage of the systems are asked from three different answers; 1) idea stage, 2) experiment stage, and 3) application stage. The number of systems in each development stage is shown in Figure 12. In the field of construction, there are many systems using Optical Fibers and CFGFRP for the purpose of health monitoring, and those systems are answered to be in the application stage. On the other hand, most of the systems in other engineering fields are answered to be in the experiment stage.

Q6. Future Research Needs
Figure 13 shows a bar chart of the number of systems for each research need. The subject of material cost is the highest need in all engineering fields. The size and power of devises are very crucial in the field of construction to control large scale construction structures.

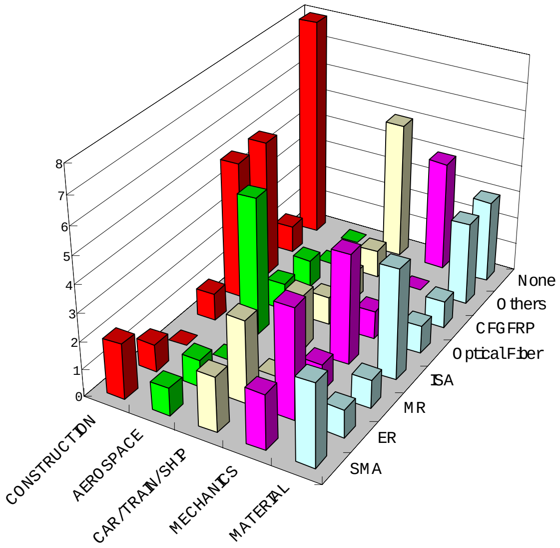


Figure 8 Smart Materials

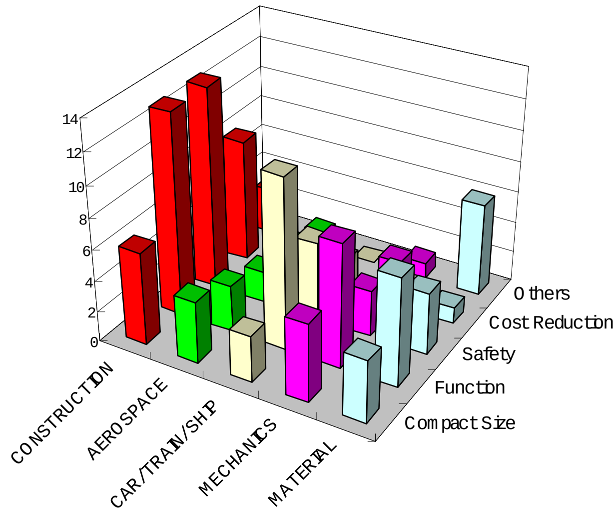


Figure 9 Objectives

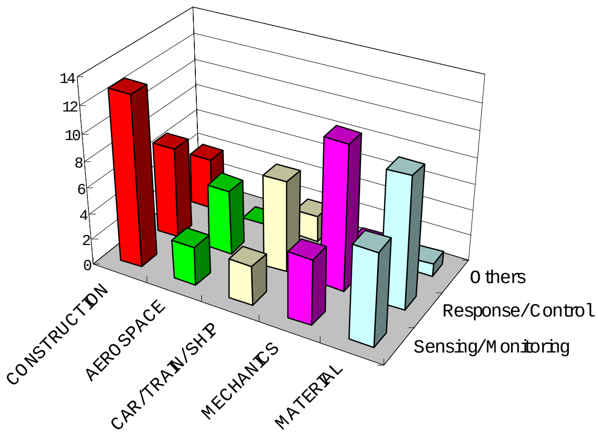


Figure 10 Functions

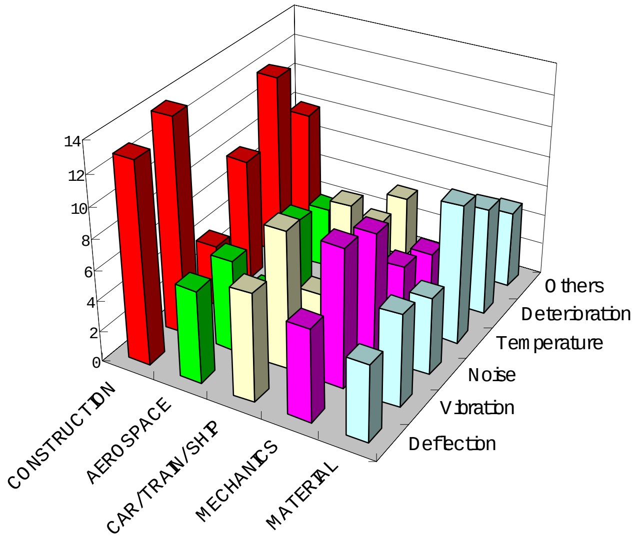


Figure 11 External Disturbances

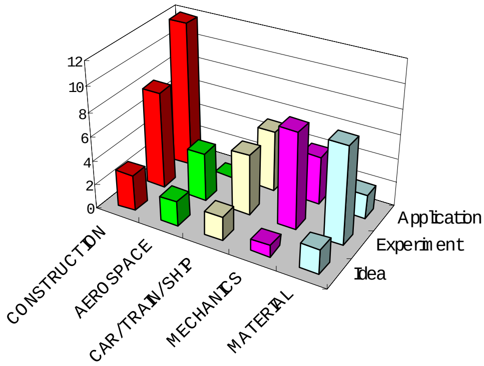


Figure 12 Stages of Development

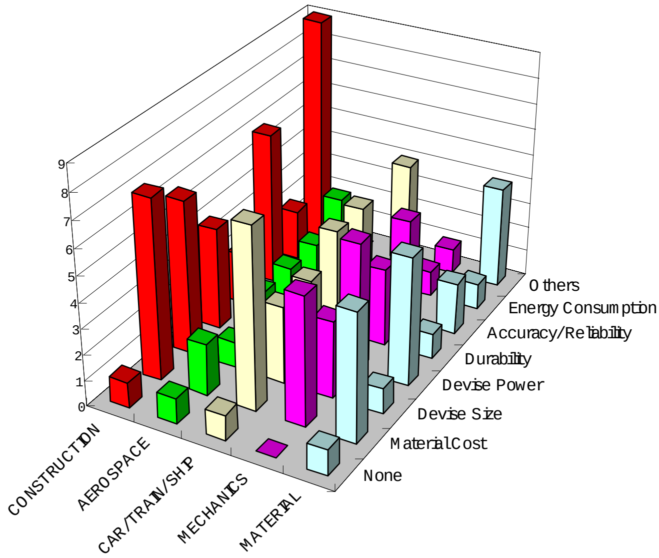


Figure 13 Research Needs

CONCLUSIONS

Building Research Institute, Japanese Ministry of Construction and the National Science Foundation, U.S.A. initiated the research and development of “Smart Structural Systems“ in 1998 as a 5-year research project. This paper summarizes the research plan and results of feasibility studies which are :

- Definition and concept of smart structural system for building structures,
- Research subjects in sensing and monitoring technologies,
- Research subjects in effector technology, and
- Survey of research and development of smart structural systems in Japan.

This research and development project aims to apply advanced technologies, such as new materials and new structural systems, to develop smart structural systems. It is expected that the project can improve the performance of buildings, reduce the expense of construction and maintenance, and eventually ensure the future sustainability of buildings.

ACKNOWLEDGEMENT

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