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TECHNOLOGY UTILIZATION GUIDELINES OF STRUCTURAL HEALTH MONITORING FOR BUILDINGS AND ITS APPLICATION

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SUMMARY

As a fruit of a 5-year research and development project of "Smart Materials and Structural Systems" as a part of U.S.-Japan cooperative research efforts, technology utilization guideline of structural health monitoring is published. This paper describes the outline. The contents are followings. (1) Purpose and state of the art of structural health monitoring, (2) Useful data acquisition from smart sensors and conventional sensors, (3) Networking and data processing, (4) System Identification, (5) Global damage detection and local damage detection, (6) Smart sensors, (7) Applications.

INTRODUCTION

Building Research Institute and National institute for land and infrastructure management 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. In this project, some sub-committees were organized to achieve the research objects. The sub-committee on sensing and monitoring technology was one of them, and it mainly had investigated an applicable damage identification method of structures by a vibration such as an earthquake motion, and smart sensor technology that measures and identifies the state and phenomena of building structures and members. In the last year among the project, 2002, the Technology Utilizing Guideline of Health Monitoring Systems [1] was proposed, in which the methods and procedures of health monitoring systems were explained. The sub-committee on sensing and monitoring technology had mainly focused on the damage detection tests on the structural models or members. Those test results formed only a small part for the practical application. Nevertheless, in the guideline, applicable health monitoring systems including experimental level systems which are rarely yet used for the structural buildings are introduced. In this paper, the outline of the technology utilizing guideline of health monitoring systems is explained.

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THE OUTLINE OF THE TECHNOLOGY UTILIZING GUIDELINE OF HEALTH MONITORING SYSTEMS

The contents of the technology utilizing guideline of health monitoring systems are as follows;
Chapter 1 Introduction,
Chapter 2 The objectives and the actual state of the health monitoring systems,
Chapter 3 Glossary,
Chapter 4 Flowchart of the technology utilizing guideline of health monitoring systems,
Chapter 5 Acquisition methods of input/output data in the health monitoring systems,
Chapter 6 Damage detection based on the model,
Chapter 7 Damage detection based on the phenomenon,
Chapter 8 The technology of the fusion of estimated results and measured data,
Chapter 9 Application examples of the health monitoring systems.

The objectives, scope, glossary and flowchart are explained from chapter 1 to chapter 4. The procedure of health monitoring systems is shown in Figure 1. A detailed explanation about the items in the enclosed part by dotted line is given, while abut the items in the outer part, only concepts are described in this guideline. In chapter 5, the method to collect input/output data is introduced along with the experimental method, the sensors including a smart sensor, and the collecting data system (data logger and wire-saving systems). Constant monitoring, monitoring after shock and monitoring during shock shown as in Figure 2 is also introduced.

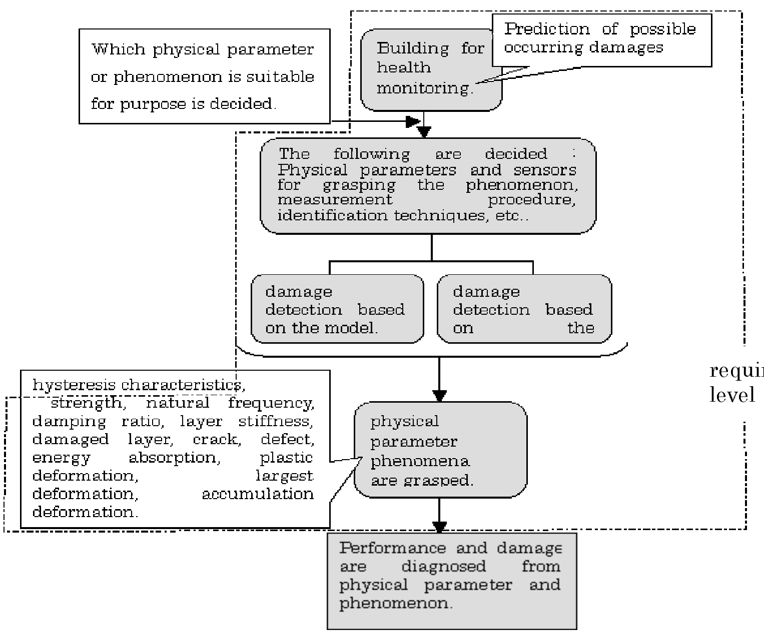

Fig. 1 Procedure of health monitoring

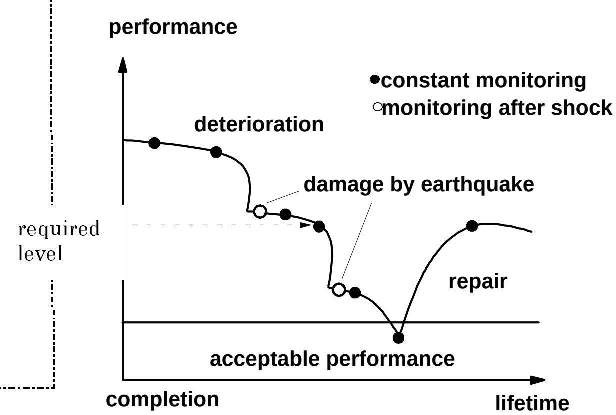

Fig. 2 Life cycle monitoring

In chapter 6 and 7, two types of the damage detection method is introduced; damage detection based on the model and damage detection based on the phenomenon. In chapter 8, the method to fuse the results of the damage detection test and analyze them is introduced.

In chapter 9, using the methods mentioned from chapter 5 to chapter8 indicates applicable examples to large-scale tests.

STRUCTURAL HEALTH MONITORING TECHNOLOGIES

Damage detection tests of five-story steel frame

Damage detection tests of five-story steel frame with simulated damages are carried out [2]. Test frame is five-story steel structure shown as Figure 3. Fiber brag grating (FBG) sensors, accelerometers, strain gauges and laser displacement meters are installed in this test frame. We assume damages by removing studs from only one story, loosening bolts of beams, cutting part of beams and extracting braces from only one story. We apply the flexibility method that is one of a damage identification method using modal properties. We apply this method to this test model. In some cases we can estimate which story is damaged, and in other cases we cannot. If the studs in the first story are removed, the first story damage indicator is large as in Figure 4. We also applied the method using multiple natural frequency shifts. Making use of the change in five natural frequencies due to damage, the location of damaged stories can be pinpointed. In both methods, we cannot identify damaged story in some cases. Some methods other than methods using modal properties have to be tried to apply in such cases.

Fig. 3 Exterior of test frame

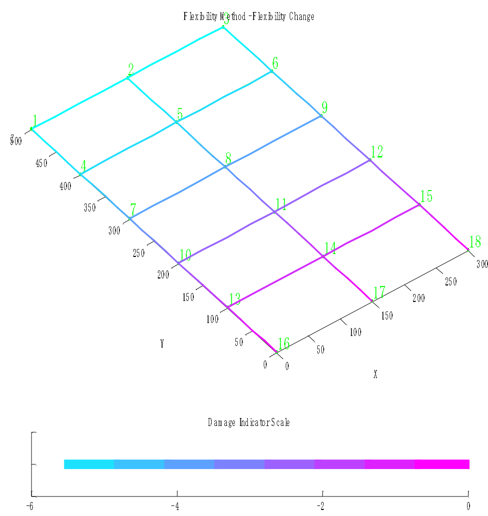

Fig.4 Flexibility changes for no studs at the 1st storv

Damage Detection Test Using Large Scale Test Frame

Shaking table test using a three-story large-scale steel structure with cementitious stud short column are carried out [3]. The test frame is shown in Figure 5. The test frame story height is 1.8m, total height is 5.4m, floor plan is 4mx3m and there are two spans in excitation orthogonal direction. Shaking table test is carried out at large-scale earthquake simulator facility of the National Research Institute for Earth Science and Disaster Prevention. Cementitious stud short column are installed in the center frame of tested structure and stud short column are actually damaged during the shaking. We carry out damage detection test on damaging stud short column and we measure the damaging process of stud short column. We apply damage identification methods to these phenomena. Two types of identification are tried. One is a) identification using the data under excitation and the other is b) identification using the data of before and after of the excitation. In both cases, we use identification method by ARX model. From identified results, natural frequency decreases, damping ratio increases and story stiffness decreases as experienced amplitude increases or input amplitude increases. Story stiffness results are shown as Figure 6. Almost all characteristics by microtremor can be estimated to be same as those by white noise. A model using stick-slip elements is proposed. Natural frequency, damping ratio and story stiffness described by this model is consistent with experimental results.

Fig. 5 Exterior of test specimen

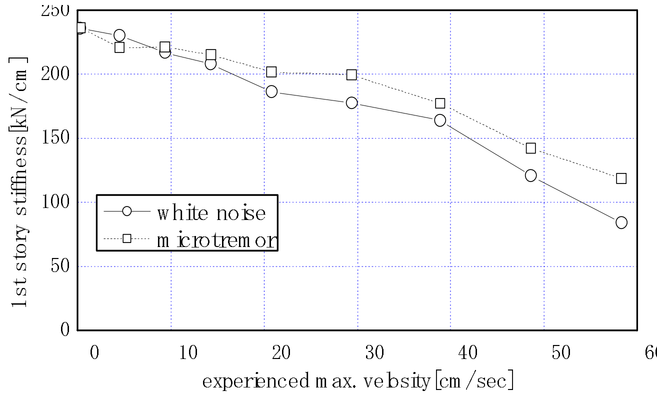

Fig. 6 Stiffness changes according to experienced max. velocity

SMART SENSOR TECHNOLOGIES

Sensors

In this guideline, following sensors are discussed.
1) Optical fiber sensors for displacement, deformation, strain, heat, and water.
2) Carbon fiber sensor in concrete for crack, strain, and deterioration of concrete.
3) Radio-Frequency Identification (RFID) Tag sensor for crack on concrete.
4) Wave sensors for deterioration of concrete.
5) Temperature sensor for plastic deformation of steel.
6) Maximum value memory sensor for displacement.
7) Two-wire sensing system with processor-built-in sensors.

Radio-Frequency Identification (RFID) Tag sensor

The original concept of this sensor was proposed by Prof. Wood [4]. This sensor consists of a IC tip with a tag number and an antenna which wire is elongated by additional wire, tape and carbon wire, as shown in Photo 1 and Figure 7. When a big crack occurs in the structural member, the aluminum tape will be broken and the RF Transmit and Receiver cannot detect the RFID Tag sensor (Photo 2~4). Only one RFID Tag sensor detected the crack occurred at the bottom of the RC member and the other sensors could not detected cracks, because almost cracks are less then 0.04 mm in width and the aluminum tapes have large ductility for crack detection. Therefore other wire materials such as small copper wires and carbon strings should be checked for detection of cracks.

Two-wire sensing system with processor-built-in sensors

Outline of composition of the two-wire sensing system for the three-story steel frame test is shown in Figure 8. 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 gages,
2) 4 channels for on-off switch for crack detection,

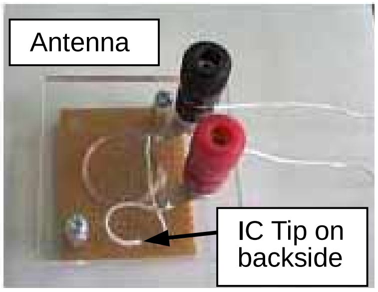

Photo 1 RFID Tag

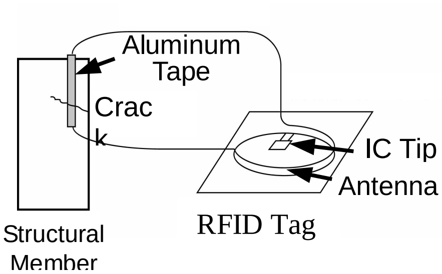

Fig.7 Schematic view of application of RFID Tag sensor to the structural members

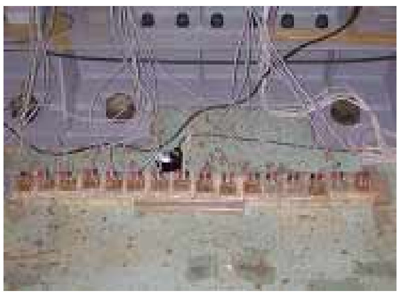

Photo 2 RFID Tag sensors

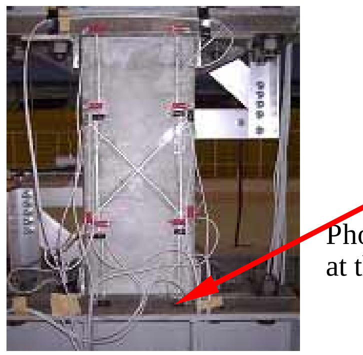

Photo 4 Broken aluminum tape at the bottom of the RC member

Photo 3 Aluminum tape for RFID Tag sensor and RC member

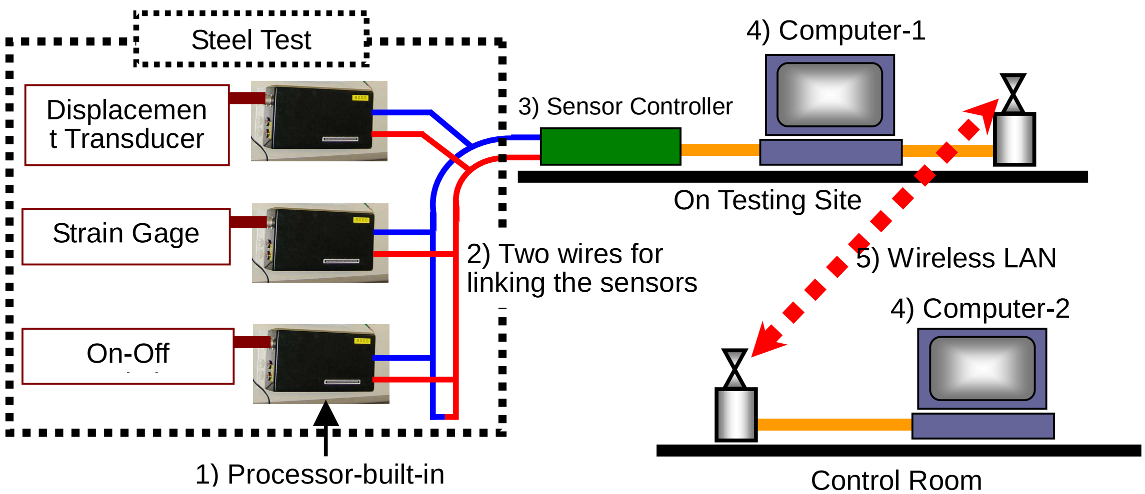

Fig.8 Outline of composition of wire-saving sensor system for the three-story steel frame test

3) 8 bits accuracy of A/D conversion,
4) 10 msec interval of A/D conversion,
5) 64 words for memory,
6) Memory for maximum and minimum values,
7) Memory for the local peak values (Figure 9),
8) Two-wire link for electric power supply and communication with controller,

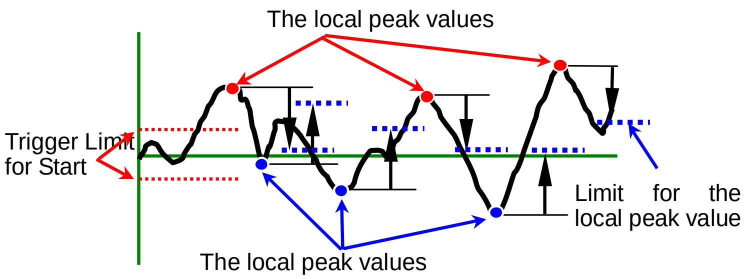

Fig. 9 The local maximum and the local minimum values

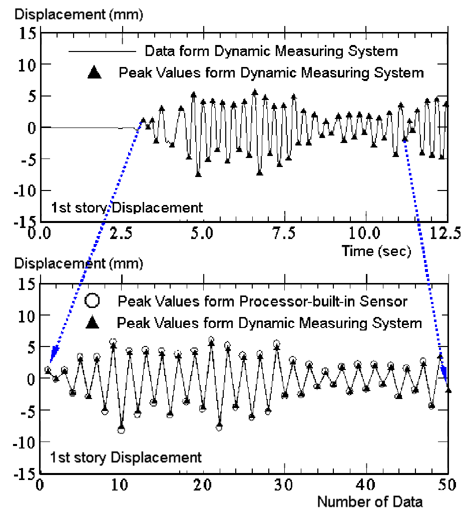

Fig. 10 Comparison of peak data obtained from the dynamic measuring system and the wiring-saving sensor system

Figure 10 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 correspondence. But this sensor does not have time information now, so we cannot get the time history but we can get maximum and minimum values, each peak values and the accumulated value of data history.

SENSOR NETWORK SYSTEM WITH RT-LINUX

SENSOR NETWORK

The Sensor Network in this paper is a measurement system of sensors installed at a part of the LAN in buildings (Figure 11).

The most important point in the Sensor Network is to have real time accuracy between the measuring of sensors. The Sensor Network is needed to guarantee the same start time of a measuring in all sensors and the same sampling time. That is why the Sensor Network uses the RT-Linux, which is an operating system (OS) with the function of the real time process. Figure 12 shows the structure of RT-Linux. RT-Linux has an added function to deal with the real time process in the high level priority among the kernel executed in OS.

The communication system of this Sensor Network uses the RT-Messenger [5], which is the new real time application that can work under the RT-Linux.

EXPERIMENT

The system of Sensor Network is shown in Figure .13. In order to test the real time accuracy of the Sensor Network, RT-Messages are served in the time interval of 1 milli-second from the server and the time delay of serving in the server and the time delay of receiving in the Client-A

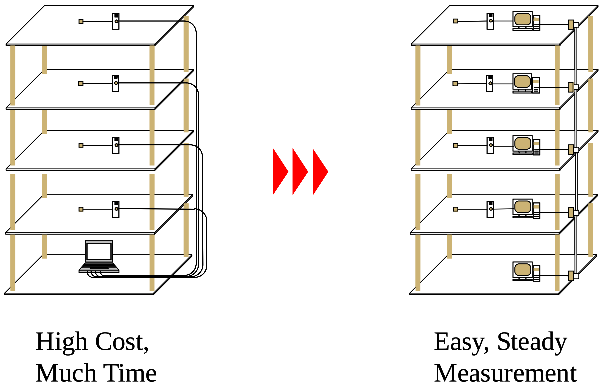

Fig. 11 Utilization of LAN instead of Wiring

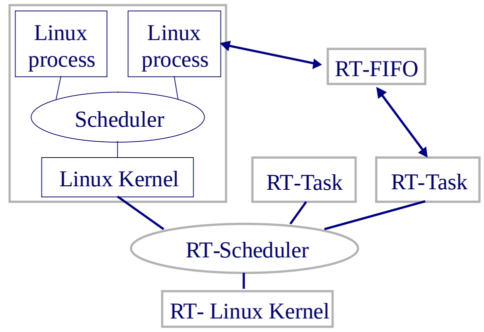

Fig. 12 Structure of RT-Linux

and Client-B are measured. As a result, the time delay of serve is 1.3 microseconds in the maximum, and the time delay of receives is 10.1 microsecond in the maximum. After the transmit command in the interval of 1 milli-second, the time interval of serve and receive is exactly measured in 1 milli-second. It means that the time delay of serve and receive is enough short against the time interval. That is why this Sensor Network has the enough real time accuracy.

And in order to verify the effects of RT-Messenger, the comparison between the system with RT-Messenger and the system without it are made. The comparison method is that 1 PC serves a packet in the time interval of 1 milli-second from RT-Task and the other PC receives the packet on RT-Task. Figure 14 shows the measuring results of the system with RT-Messenger.

In the system without RT-Messenger, at the side of server, the ratio, which the time interval is 1 milli-second, is about 10%, and the tolerance is large. At the side of receiver, the ratio that the time interval is 1 milli-second is lower than 5%, and the tolerance is large.
Finally, RT-Messenger is necessary for the “Sensor Network” which requires the real time accuracy.

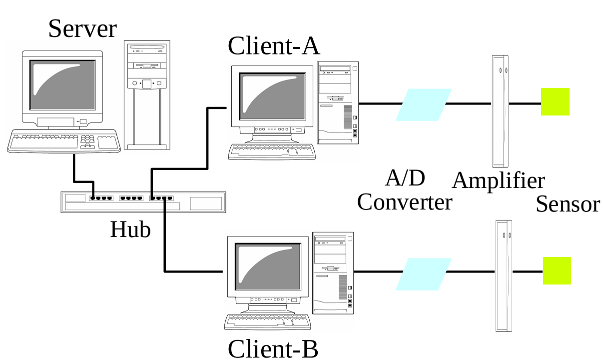

Fig. 13 System of sensor network

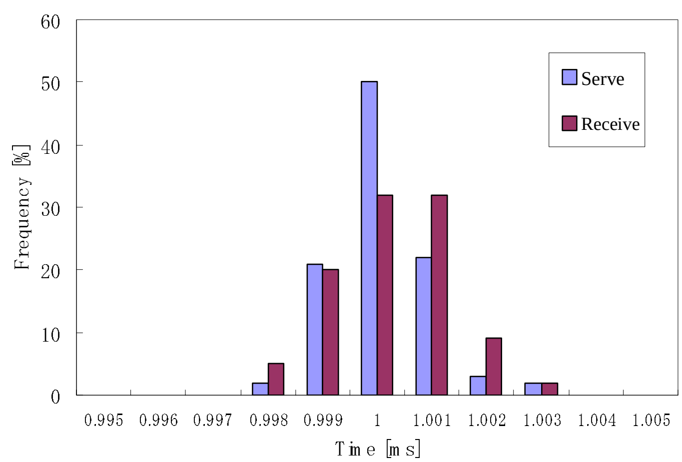

Fig. 14 Time intervals with RT-Messenger

CONCLUSION

The outline of the technology utilization guideline of structural health monitoring; one of the accomplishments of 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 was explained. The investigation done by sub-committee on sensing and monitoring was mainly focused on. The other methods often used by existing research were also described. The applicable method in this guideline and its results were also indicated.

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