

Structural health monitoring of bridges in Japan: an overview of the current trend

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ABSTRACT: This paper describes an overview of research and development on structural health monitoring (SHM) of bridges in Japan. The paper consists of three parts. The first part presents the backgrounds of SHM development, in which the needs for bridge SHM are explained. In the second part, the concept of SHM as a part of vulnerability assessment in conjunction with risk reduction is discussed. Key development in SHM such as sensor technologies and methodologies are reviewed. The third part of the paper outlines strategies implemented for bridge SHM in Japan. They are categorized into three main groups according to the purpose of monitoring that is for: natural hazard and environment condition, effective stock management, and failure prevention. Finally the paper presents examples of bridge monitoring systems toward implementing these strategies and the lessons learned from monitoring experiences.

1 INTRODUCTION

Japan transportation infrastructure was mainly built during the post-WWII rapid economic growth between 1955 and 1975. After 1950s, there are approximately 650,000 bridges of 1,150,000 km constructed in a 370,000-square kilometer of country area (MLIT 2005). This massive infrastructure network provides essential services to support sustainable economic growth, productivity, and well-being of the nation.

Development of bridge monitoring is an integrated part in an effort toward realizing a reliable and sustainable transportation and infrastructure system. Due to severe environmental conditions and frequent natural disasters, early initiatives in bridge monitoring were focused on conditions and loadings to ensure the safety. Recently, the bridge SHM has evolved into a more comprehensive program as a part of infrastructure management. In this context, evaluations of bridge structural performance and/or existing damage are the essential part of rational and efficient stock management. Realizing the importance of this issue, bridge SHM has attracted interest of many researchers, universities and industries.

The paper attempts to review the ongoing research activities related to SHM of bridges in Japan. It firstly presents backgrounds of the problems faced by Japan's infrastructure, especially bridges. Following that, a concept of bridge monitoring and the role of SHM as a tool for risk reduction are described. The paper describes several strategies in bridge SHM with examples of the systems that are still on the research and development stage, and the ones that are already implemented in practice.

2 DEVELOPMENT OF BRIDGE SHM IN JAPAN

2.1 *Monitoring for natural disaster: early initiative*

The natural disasters are some of the major concerns for civil engineering construction and maintenance. Early initiative for bridge monitoring in Japan was highly influenced by natural disaster. The facts that geographically Japan is prone natural disaster such as earthquakes and typhoon, and severe environment condition such as strong wind and high humidity, have made loading and condition monitoring especially for large bridges a common practice. In this context, the scope of monitoring has been to monitor two major aspects: load effects and structural response.

Kobe earthquake in 1995 is an example how a natural disaster has shaped the design practice in civil engineering in Japan. The earthquake that killed more than 6000 people and caused financial loss at around US\$ 131.5 billion, caused extensive damage to highway bridges in the national highway and local expressways network. To anticipate the similar scale of earthquake in the future, bridge seismic design code was later revised. Constructions of new bridges are subjected to the new code, while the existing bridges are undergoing seismic assessment and retrofit program to meet the demand required in the new code. The retrofit program consists of two phases. The first phase of the program mainly retrofits ordinary bridges and it was emphasized on bridge piers and girder restrainers. In the second phase, many large bridges are currently being retrofitted. Fujino et.al (2005), for instance, outlines the retrofit plan/design of three large cable-supported bridges in Tokyo.

In the context of a bridge retrofit and seismic assessment program, structural health monitoring (SHM) plays an important role. Many bridges in Japan especially the long-span ones are instrumented with permanent sensors. This instrumentation provides seismic or/and ambient responses that are essential to obtain insight into the real behavior of bridges during different loading conditions.

Another geographical aspect that influences Japan infrastructure, and bridges in particular, is the country's topography. As an archipelago country, Japan consists of mountainous islands with population mainly concentrated near the seashore. Therefore, transportation infrastructures including many bridges are built near the coast line, and some are crossing the channel, such as the world longest Akashi-Kaikyo Bridge. Due to this condition, some bridges are situated at severe environmental condition and subjected to deterioration caused by high chloride intrusion and humidity. Consequently, maintenance and monitoring system must be employed to control the environmental effects and to prevent further deterioration

2.2 Bridge stock management

In the past few years, evaluations of structural performance and/or damage of existing bridges have become more and more important for rational and efficient stock management. To understand this condition, we will review the current situation of Japanese infrastructure stock.

The peak of Japan's infrastructure development occurred between 1955 and 1975. During this time, rapid economy growth accelerated public spending on infrastructure, and as a result Japan's infrastructure stocks have accumulated significantly. The rush to expand infrastructure during the rapid economy growth has led to cost-cutting by sometimes using minimal materials needed for the structures' expected performance. Bridges provide an excellent example of the problem. Deterioration is an issue for many highway bridges in Japan, which were mainly built around 1970s (Fig. 1(a)).

Awareness of the current condition of bridges has emerged recently, triggered by the findings of steel member fractures in the Kisogawa Ohashi Bridge, Mie Prefecture, in June 2007 and in the Honjo Ohashi Bridge, Akita Prefecture, in August 2007. The sudden collapse of the I-35W interstate bridge in Minnesota, United States that followed later in August 2007 has only intensified the concern, considering similarity of the two bridges in Japan with the one that collapse. Many believe these two incidents are the tip of the iceberg of the problem.

Figure 1(b) shows the composition of bridge and the total number of bridge. It can be seen that starting from 2025 many Japanese bridges will be more than 50 years of age. This concentration may induce simultaneous deterioration of large portion of the stock and would lead to a high social cost.

Adding to the problem of aging bridges is the drastic increase of traffic density. The daily traffic volume in major highways can reach as high as 15,000 vehicles per lane, in which the ra-

tio of heavy trucks is also high, in some case is as high as 30% (Fujino 2005). The high intensity and frequency of loading generated by this high traffic volume generates many problems in bridges. The most typical problem is fatigue damage in concrete slabs and steel welded girders.

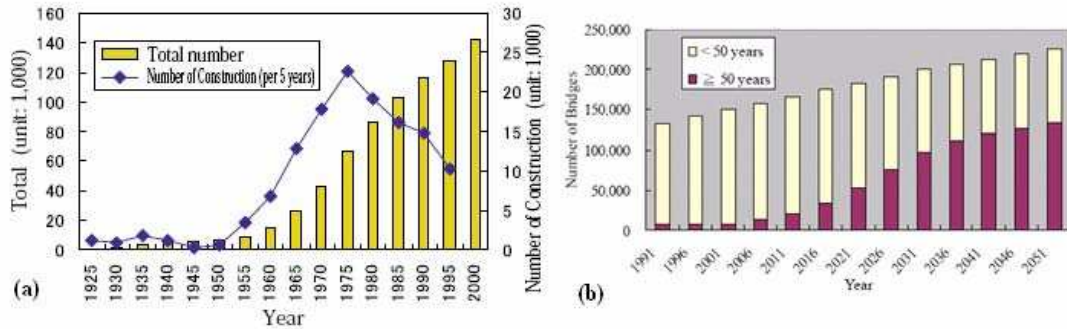


Figure 1.(a) Total number of highway bridges and construction year in Japan. (b) Composition of bridge's age to the total number of bridge in Japan.

Failure to recognize the importance of maintenance can be noted from insufficient investment allocated to infrastructure maintenance. Report (Fujino and Takada 2008) shows that many local governments spend less than 1%, or even less than 0.5% of the total assets for bridge maintenance expenditure. And this insufficient maintenance expenditure is expected to continue in the following years due to the budget constraints.

Constant threat of natural hazard and severe environmental conditions, compounded by the deterioration due to aging infrastructure force extra efforts and strategies for maintenance. These are the motivations for bridge structural health monitoring in Japan

3 POTENTIAL BENEFIT OF BRIDGE SHM

3.1 Rationality of structural monitoring for risk reduction

Concept of bridge monitoring or structural health monitoring in general can be viewed as an integrated strategy for risk reduction. In this context, risk is defined as the function of two quantities: hazard and structure vulnerability, in the form of:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \quad (1)$$

Hazard, defined as the probability of occurrence of unexpected events that may endanger the structure, is spatial and temporal dependent. Conventional practice assumes that the structural vulnerability is time-invariant, and a function of structural configuration such as system redundancy, ductility, materials, and quality of construction, all of which are designed at the construction phase. In reality, however, structural vulnerability is also temporal dependent in that it may differ from time to time due to deterioration, aging or changing in environmental and loading conditions.

The methodologies for performing hazard analysis and monitoring have been well-developed and are well-established. On the other hand, approaches to quantify a time-variant structural vulnerability are still in under research and development. An example of conventional approach to structural vulnerability assessment is the fragility curves. While useful, the empirical fragility curve is sometimes inadequate due to its limited events and observed damages. Therefore, the analytical-based fragility curve is developed for a more general use of vulnerability estimation.

This approach also has some significant limitations. Since the curve is computed based on a normal distribution assumption, one can never be certain about the exact position of the studied structure in the given distribution. To minimize uncertainties, field monitoring is the feasible option. Using monitoring the actual structure condition can be assessed and therefore its vulnerability can be quantified.

3.2 The need and use of advance sensor technologies for monitoring

Until recently, monitoring –in the form of inspections, of bridges were commonly considered to be old fashioned, low-tech and time consumptive. They rely mainly on visual inspection that can be subjective and inaccurate. Recent development in sensing, communication and information technologies, however, may completely modernize the inspection procedures and increase significantly the efficiency by reducing the amount of labor and working time.

In recent years, innovations have led to the development of high-tech-based systems that are based on the principle of *sensing* the structural condition or loading, *transferring* the measured quantities through communication system to support a knowledgeable *decision making*. With such advanced systems, large amount of infrastructure can be managed more effectively and potential losses or failures can be minimized.

The use of advanced sensor technologies for monitoring is a very important issue for Japan. Considering the increasing number of aged population and decline in the birth rate, it is expected that Japan will face a serious labor shortage in the near future. This problem will also affect the strategy in infrastructure management. In the future, programs that depend extensively on manpower should be avoided, and instead shifted to those that are based on more advanced technologies.

There are two fronts of research in monitoring that are currently active, namely sensing technologies, and structural diagnostic/prognostic. The former typically deals with sensor types and systems, data acquisition, data processing, communication, management and storage. The latter deals with data analysis and interpretation, system identification, local and global diagnostic, defect/damage detection and remaining life prediction, all of which are represented by performance indicators.

In authors' opinion, regardless the type of sensor and technology, there are two aspects need to be considered when choosing sensor for monitoring civil infrastructure:

1. Scalability. As mentioned in the previous section, in term of scale, civil infrastructures lie within two extreme boundaries: the macroscale extreme and the microscale extreme. This also applies to the selection of hardware for monitoring. At one end, when it comes to a macroscale such as the global scale, sensors linked to satellites in the global positioning system (GPS) are used. On the other hand, for the microscale problem, sophisticated nano or micro sensors are more suitable. The civil infrastructure scale is considered on the mesoscale level. Because of the spatial diversity and sheer numbers of structures, the use of a too-expensive and sophisticated microsensing system should be avoided. At the same time, however, the uniqueness of information of each structure system should be retained.
2. Durability. Civil infrastructures are designed to last for a long time, typically over 50 years. During the service life, hazardous events may not occur very frequently, but nevertheless the monitoring system must be always up and running. This indicates the need for not only reliable but also durable sensors.

On the structural diagnostic/prognostic front, the methodologies can be categorized according to the scope and type of analysis. The scope of analysis consists of: (i) microscopic monitoring, where damage detection and localization are of main interest; and (ii) macroscopic monitoring, where holistic structural integrity and its comparison are the main focus. While the microscopic monitoring is the conventional mainstream of structural health monitoring and advancing steadily, macroscopic monitoring is recently attracting interest especially from practical point of view to connect health monitoring and existing inspection methodology.

4 BRIDGE MONITORING: STRATEGIES AND EXAMPLES

Bridge monitoring system has different strategies according to the demands. This section describes strategies and examples of bridge monitoring that involve authors and their associates. They can be broadly categorized into three groups: monitoring for environment and natural disaster prevention, monitoring stock management, and for failure prevention.

4.1 Monitoring for environment and natural disasters prevention

4.1.1 Bridge seismic monitoring

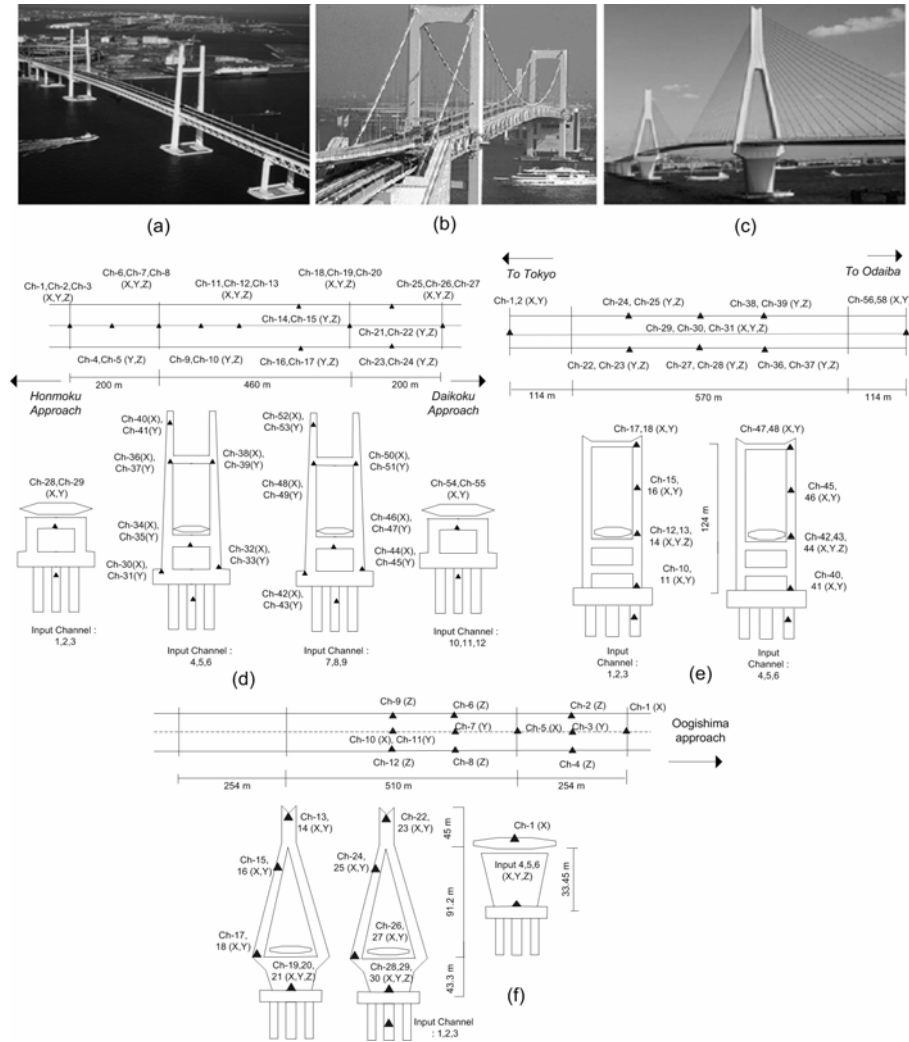


Figure 2 (a) Yokohama-Bay Bridge (b) Rainbow Bridge (c) Tsurumi-Fairway Bridge. Vibration sensor network of accelerometers at: (d) Yokohama-Bay Bridge (e) Rainbow-Bridge, and (f) Tsurumi-Fairway Bridge.

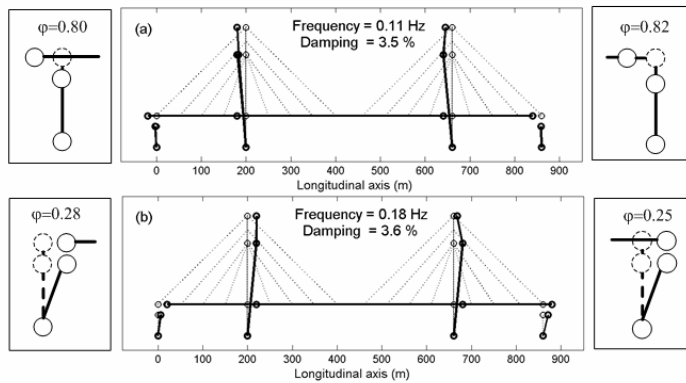


Figure 3 Two typical first mode of Yokohama-Bay Bridge identified from seismic records (a) hinged-hinged mode (b) fixed-fixed mode

Monitoring for seismic response has been widely employed especially for structures with special features such as long span bridges (Yasuda et.al. 2000), and bridges with new technology such as base-isolated bridges (Chaudhary et.al 2000). Three instrumented long-span bridges in Tokyo area become subject of the recent study by (Siringoringo & Fujino 2008a). The three bridges are permanently instrumented with accelerometers and seismic records were analyzed regularly to monitor the bridges condition.

The first bridge studied is the Yokohama Bay Bridge, located at the entrance of Yokohama harbor (Figure 2.a). It is a double-deck steel –truss box cable-stayed bridge with a central span of 460 m and two side spans of 200 m each. The bridge, completed in 1988, has two H-shaped towers 172 m high and 29.25 m wide. Eighty-five sensors measuring acceleration and displacement are installed at 36 locations throughout the bridge. Along the girder, sensors are installed at 9 locations with spacing of 115 m (Figure 2 d).

The second bridge is the Rainbow Bridge, (Figure 2.b) completed in 1993. It is a double-deck suspension bridge that connects the Shibaura Wharf with Odaiba, Tokyo. The bridge has two H-shaped towers with a height of 125.6 m at the Shibaura side and 124 m at the Odaiba side. The 3-spanned girder is composed of a steel truss with side spans of 114 m each and a middle span of 570 m. The upper deck, which is 9.25 m x 2 m, is used for highway traffic while the lower deck, which is 7 m x 2 m, is used for a monorail system. The bridge is instrumented with 64 sensors that consist of accelerometers and displacement sensors (Figure 2.e).

The third bridge is the Tsurumi Fairway Bridge, a three-span single-plane cable-stayed bridge. The girder consists of two 255 m side spans and a 510 m center span. It is characterized by two inverted Y-shaped towers that are each 183 m high and 40 m wide at the bottom. Completed in December 1994, the bridge is currently the longest single-plane cable-stayed bridge in the world. For monitoring purposes, fifty accelerometers are installed on the bridge (Figure 2.f).

Dense seismic measurement systems installed on these bridges are very useful to capture real behavior of the bridge during various levels of earthquake. The study shows that by employing a system identification technique, performance of dynamic characteristics of the bridge can be evaluated.

Observation of seismic response recorded on Yokohama-Bay Bridge revealed that in addition to global behavior such as amplitude dependency of damping ratios, variations of local components were also observed. The identification results of the Yokohama Bay Bridge revealed two types of the first longitudinal mode, with main difference in relative modal displacement between the end-piers and girder (Figure 3). At these locations, the end-piers and girder are connected by link-bearing connections (LBC) whose essential function is to prevent the large inertial force of superstructure from being imparted to substructures during large excitation. For this purpose, the LBC is expected to function as a longitudinal hinge connection to indicate that the girder and pier caps work as separate units.

Two types of longitudinal mode indicated variation from the expected performance. The first mode that exhibited a large relative modal displacement revealed characteristics and frequency that were very close to that of the analytically obtained first longitudinal mode. The large relative modal displacement suggested that the hinge mechanism might have had occurred. On the other hand, the second mode, exhibited smaller relative modal displacements between end-piers and girder indicating that the LBCs had yet to function as full-hinged connections. As a result stiffer connection and higher natural frequency were identified. These results indicate that performance of LBCs depend on the amplitude of earthquake excitation and does not always follow the analytical prediction.

Although the study was focused on comparison with design and analysis, the result implies that malfunction or unintended-function of the bearing could be detected by the monitoring system. In addition, this result is reflected to the on-going seismic retrofit of the bridge, connecting the girder end to the footing by PC cables.

4.1.2 Bridge environment monitoring: wind monitoring

Monitoring for wind-induced vibration has also been widely employed especially for long span bridges in Japan. Portable as well as embedded sensor networks are utilized to measure wind condition and dynamic response of the bridge. Such measurement system was employed at Ha-

kucho Bridge (Fig. 4). Using dense array of sensors wind-induced ambient vibration was measured for a few days under various level of wind speed (Nagayama et.al 2005, Siringoringo et.al. 2008b). Ambient vibration measurement is an important tool to evaluate the integrity of in-service structures.

The measured data clearly show the quadratic relationship between wind velocity and response. A two-step structural identification method that consists of: identification of vibration modes and inverse analysis of structural properties from the identified modes was employed. For modal identification, the method treats the structure as a multi-input-multi-output system, distinguishing noise from true modes and employing ambient vibration measurement. For the identification of structural properties, assumptions on proportionality of damping, previous estimation of structural damping/stiffness, and numerical iteration are not required. The results confirm that the method can precisely determine the characteristics of not only the lower modes, but also the higher modes, and can effectively detect changes in the structural properties. Figure 6 shows the identified aerodynamic stiffness and damping, which are usually measured in wind tunnels, but difficult to obtain in situ.

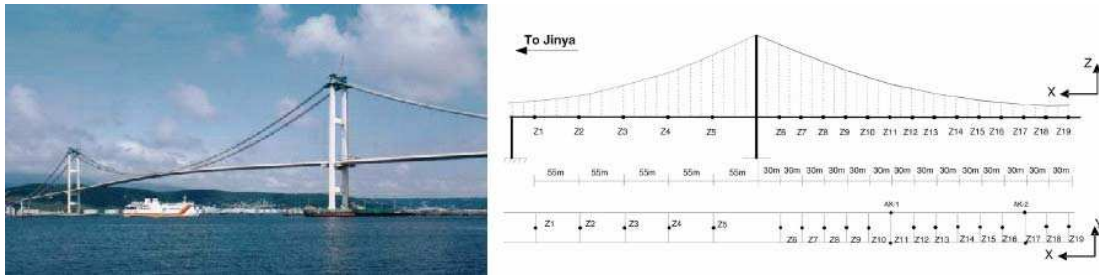


Figure 4. Hakucho Suspension Bridge and its sensor arrangement

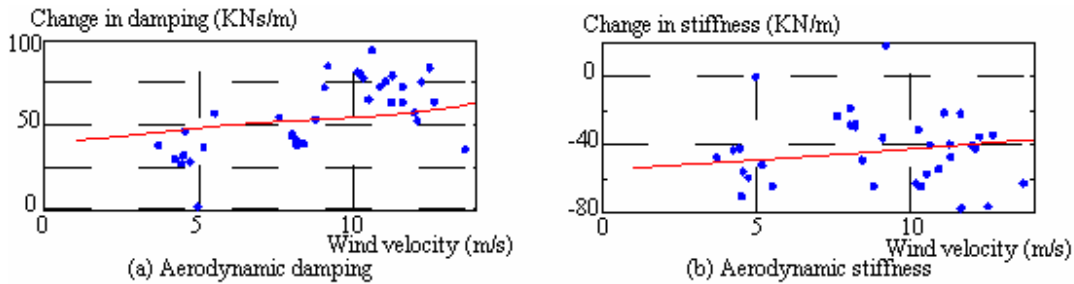


Figure 5. Relative changes of stiffness and damping with respect to wind velocity resulted from inverse analysis and wind tunnel experiment

The phase difference exists between the measuring point closest to the main tower and at the center of the main span is large when the acceleration's root-mean-square is very small. This phase difference indicates the non-proportionally damped of the system, which mainly come from the friction force at the bearings, expansion devices located at the main tower, and the aerodynamic force.

In the work by (Nagayama et.al 2005), effects of aerodynamic force and friction force were verified by employing an inverse identification technique. It was found that the contribution of aerodynamic force was smaller than the effect of friction force from the bearing. The aerodynamic force contribution is in order of one-percent when compared to the contribution of the friction force (Fig 5). These results are consistent with the expected increase in equivalent stiffness and decrease in damping when the amplitude level is small enough to suppress any relative movement at the bearing or extension devices.

4.2 Monitoring for stock management

In order to realize an efficient stock management, monitoring should be focused on performance evaluation of the condition of the stock. Performance evaluation of a bridge is essential to assess functionality, predict the deterioration and the possible failure mode, update the performance prediction, and decide the future inspection of retrofit plan. For these purposes, new monitoring systems using advanced sensor technologies are expected to improve the conventional inspection procedures. In this section, examples of monitoring for stock management are briefly discussed. They are: a) continuous monitoring of a workhorse bridge; b) Non-contact monitoring system of Shinkansen viaduct by laser Doppler vibrometer; and c) routine inspections of railway and highway by intelligent monitoring system.

4.2.1 Continuous monitoring of a workhorse bridge

Monitoring of short to medium span bridges, which are the major portion of the stock is essential for efficient stock management. For this purpose, selecting the appropriate sensor, processing and interpreting the large number of data are of great challenges for engineers. The study in (Xia et.al. 2004) demonstrates how to apply some available algorithms to the data measured by a practical structural health monitoring system and how to evaluate the results for a simple ordinary medium span bridge (Figure 6).

Identification of dynamic characteristics, temperature effects, and fatigue damage evaluation were studied using monitored data. Using dynamic response, bridge dynamic characteristics and their relationship to the traffic characteristics can be examined. The linear cumulative damage rule was applied to the stress spectrogram data for approximately one month. For certain components, the expected fatigue life was found to be much shorter than the respective design value. Maximum daily stresses were analyzed using extreme value distribution models. General Extreme Value distribution fitted the data very well and predicted the maximum compression stress of the components in the future. It was observed that the stress levels are rather high, indicating the necessity of a careful inspection.

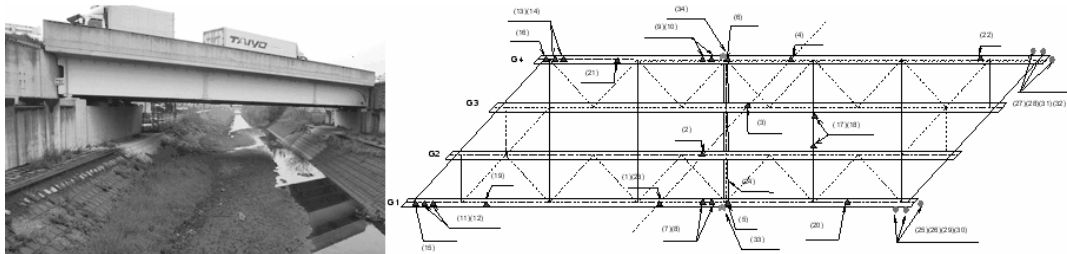


Figure 6. Workhorse bridge and its monitoring system

Overall results indicate that the structural condition is deficient and that further special inspection is required, even though the bridge itself was relatively new (12 years old). The deficiency would be related to the skew effect, which may have not been appropriately treated in design. The demonstrated implementation and methodology can be considered as the general basis for monitoring of common workhorse structures.

4.2.2 Automatic and non-contact monitoring of Shinkansen viaduct

Many viaducts that support the Shinkansen networks are made of reinforced-concrete or steel, and were constructed over 40 years ago. They are subjected to increasing service loads as a result of increasing volume and speed of the train. Because of the huge amount of kinetic energy carried at the high speeds, the train may interact significantly with the viaduct and even resonate with it under certain conditions. This mechanism may affect the safety of the passengers on board as well as the viaduct and supporting structures.

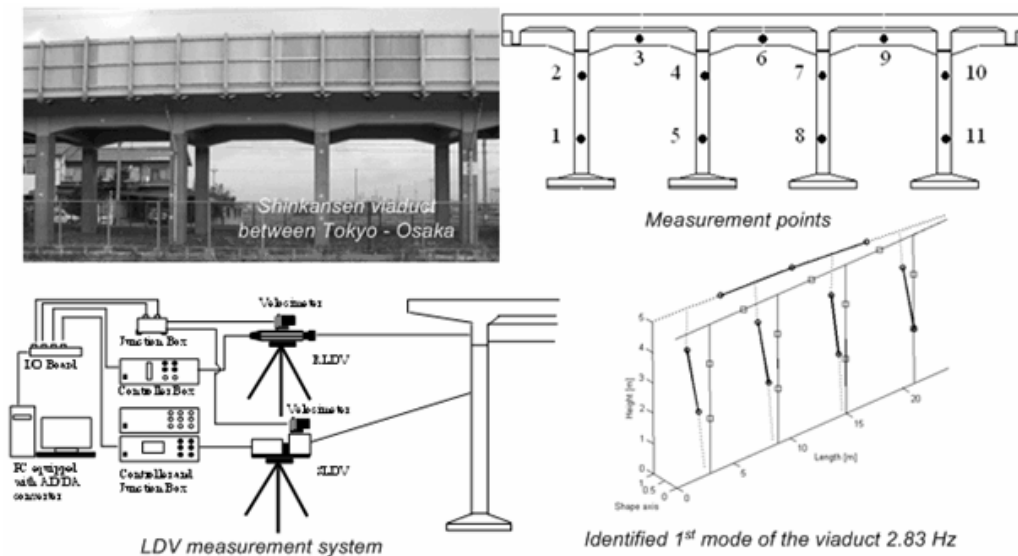


Figure 7. Shinkansen viaduct monitoring system using ambient vibration and LDV system

The influence of train speed on the structure was studied using a non-contact measurement system by means of laser Doppler vibrometer (LDV). This system was developed so that dynamic response of the viaduct can be measured in three-dimensional wise with high sensitivity (Miyashita et.al 2007). The measurement system was applied to clarify the effect of train speed on the local stress at the vertical stiffener of the lower flange of steel viaduct's girder. It was confirmed that the vertical crack at the welded portion was due to the stress changes caused by the various train speeds, and therefore retrofit measures must take this factor in to account.

Another important aspect is the evaluation of conditions of viaducts columns. As a part of scheduled structural evaluations and after the occurrence of earthquake, supporting structures namely, columns and girders are inspected. The current technique employed by Japan Railway is based on frequency analysis of the column modes. In this system, the structures are excited by impact hammer and the responses at several locations on the columns are measured. In the study by (Hernandez et.al. 2006), an automatic non-contact inspection system using LDV is proposed. Despite the difficulty in separating the column's local modes from viaduct's global mode, the study shows that by carefully analyzing the column local mode (Figure 7), one can evaluate the column as well as the integrity of its substructures.

It should be mentioned that the Shinkansen-viaduct monitoring system described here does not employ a continuous monitoring in the sense that the structure is not permanently installed with sensors. The monitoring system was developed using LDV as an alternative to the conventional contact monitoring that is time-consuming and requires massive manpower. With LDV an automatic non-contact inspection system can be realized. The automatic and non-contact characteristics of this system are particularly useful considering the amount of work.

4.2.3 Monitoring to enhance routine inspection: VIMS and TIMS

Demands on public transportation infrastructure and higher service rise as people expect higher standard of life and public service. To meet these demands, maintenance of transportation infrastructures such as railway and highway is a vital instrument. However, as mentioned above, not all infrastructure authorities or operators have sufficient operational budget. Due to budget constraint, local railways operators, for instance, cannot implement a sophisticated and costly maintenance strategy such as the one employed for the bullet train railway. Instead, they employ a system that relies on manual track profiler, whose accuracy and efficiency are limited. A simple, low maintenance cost with sufficient accuracy is therefore required.

To fill the need, the Train Intelligent Monitoring System (TIMS) was developed (Ishii et.al., 2006). The system consists of: 1) a triaxial accelerometer mounted on floor of train's car to

measure train acceleration, 2) a Global Positioning System (GPS) sensor to locate train position and, 3) a portable computer to record position and response data (Fig. 8).

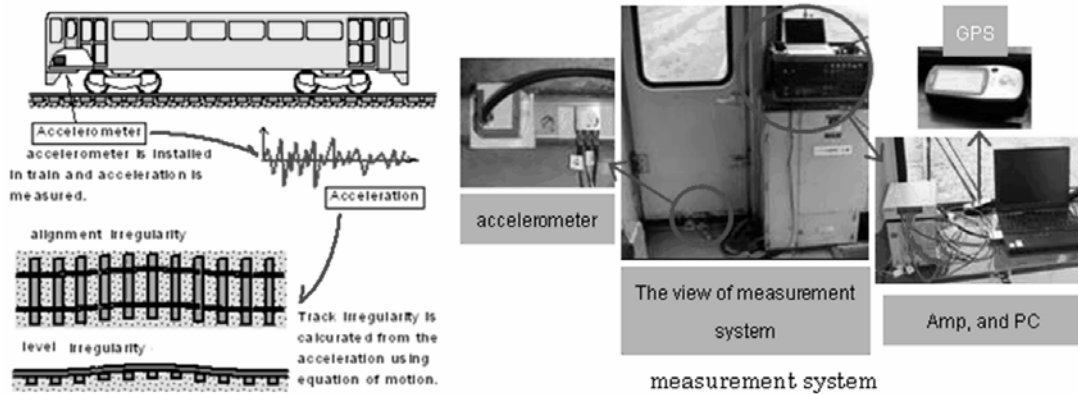


Figure 8. Train Intelligent Monitoring System (TIMS)

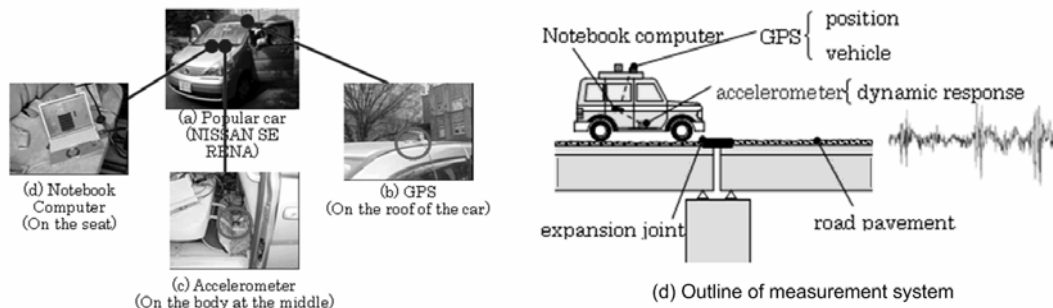


Figure 9. Vehicle Intelligent Monitoring System (VIMS)

The objective of TIMS is to improve current routine inspection system in detecting railway track's irregularity by using the vibration technique. The system is installed on a train and responses are recorded and analyzed regularly. By looking at the root mean square (RMS) of the acceleration responses, one can evaluate the response characteristics at a particular location. Location information is determined by GPS. With repetitive measurements, the equal response characteristics are expected. The distinct change on the response may then be attributed to the change in railway surface. Using this monitoring system, repair and deterioration of track beds can be tracked-down.

The facts that the system is portable and compact make it suitable for application on ordinary trains with relatively low cost. The system was applied to a local railway in Chiba prefecture and measurements with different time instances were compared. Promising preliminary results were obtained. Further development of this system is still under ongoing research and more improvements are expected.

A similar monitoring system was developed to monitor the highway pavement and expansion joints. The Vehicle Intelligent Monitoring System (VIMS) (Fujino 2005) utilizes dynamic response of a car to capture the condition of road pavements surface as well as the expansion joints. The system is proposed as an alternative to the conventional road profiler system, whose operational cost is relatively high. The VIMS system consists of: 1) an accelerometer to measure the dynamic response of the car, 2) a GPS sensor to identify the position where the dynamic response is recorded, and 3) a portable computer to store the measurement data (Fig 9).

Using the acceleration response and the pre-established correlation functions between the response and road surface roughness, one can identify the condition of highway surface from measured response and its location from GPS sensor. Furthermore, by comparing the amplitude of dynamic response and the correlation function, one can continuously monitor the condition as well as the possible defects on expansion joints. This system was applied to the Tokyo Metro-

politan Expressway, and its effectiveness to the road maintenance, i.e., frequent monitoring of the conditions of road pavement and expansion joints, was confirmed.

4.3 Monitoring for failure prevention

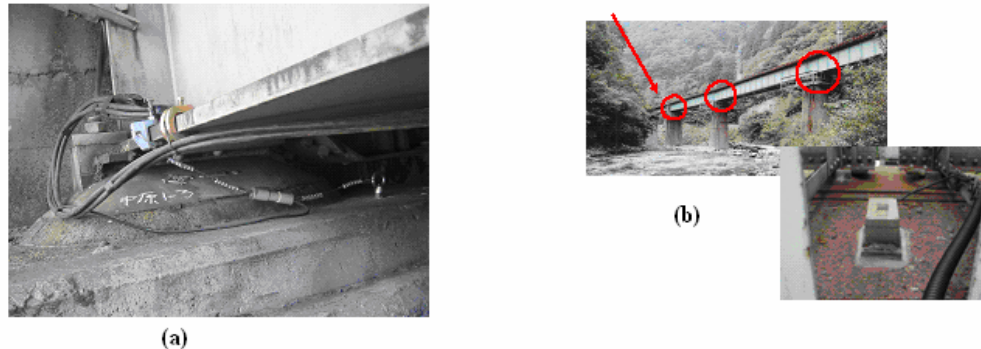


Figure 10. (a) Bridge unseating sensor, (b) Clinometric type bridge scouring sensor

Monitoring can also be directed to prevent structural failure. For this purpose, possible failure locations and circumstances under which the failure may occur should be identified a priori. When the failure mode of interest is identified or specified, monitoring system is implemented by selecting the appropriate sensor. Some of failure modes are localized, and so are the locations of sensor. Several such systems are developed and implemented for safety of railway operation.

Figure 10(a) shows an example of monitoring to prevent bridge failure due to unseating. The system is installed at the overpass bridges above highway where collision risk is considered high. When unseating of bridge girder occurs, the sensor breaks and an electrical signal is transmitted to the highway operator to suspend operation.

Another example of this type of monitoring is the scour-induced collapse detection. Figure 10 (b) shows clinometers installed at bridges to detect scour induced collapse of bridge piers (Kobayashi et.al 2002). This system works in such a way that when the inclination reaches the maintenance limits of track irregularity an alarm is sent to the operator, so that further check and countermeasures can be taken.

5 CONCLUSION

This paper discussed development of bridge monitoring in Japan. Two major factors that motivate the bridge SHM are natural disaster and efficient stock management are described. To improve bridge safety, several monitoring technologies for risk and vulnerability are implemented. In this concept, structural health monitoring serves as a tool for vulnerability monitoring. The trends in sensor technologies and monitoring methodologies are also discussed. Both research fronts are currently very active and they are expected to bring more benefits in monitoring and maintenance of infrastructure in near future.

The paper outlined strategies implemented for bridge monitoring systems in Japan. They are categorized into three main groups according to the purpose of monitoring that is for natural hazard and environment condition, effective stock management, and failure prevention. Bridge monitoring for hazard and environment involves instrumentation for seismic and wind monitoring. Examples of seismic monitoring of long-span cable supported bridges such as Yokohama-Bay Bridge, Rainbow Bridge and Tsurumi-Fairway Bridge, and wind monitoring of Hakucho Bridge are presented. Even though these monitoring systems were initially intended to measure loading, studies presented in this paper indicate the usefulness of these measurements for evaluation of structural integrity.

Monitoring technology is also being developed to improve efficiency of stock management. Applications of monitoring technologies for common workhorse bridges, Shinkansen viaducts,

and improving routine inspection of highway and railway bridges are described. Finally, to prevent structural failure, specified and localized monitoring technologies are implemented.

It is realized that structural evaluation of a bridge is a complex process consisting of a series of integrated systems, components, and procedures. At the same time we are responsible to convince that bridge monitoring is not only *fashionable* but also *vital* for our bridges and that all bridge' stake-holders gain benefit from monitoring. An ideal bridge monitoring system requires the development of integrated administrative and proven engineering solutions that are technically reliable and financially feasible. Future development of bridge SHM, in authors' opinion, should be directed toward implementing this goal.

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