THE NEEDS FOR ADVANCED SENSOR TECHNOLOGIES IN RISK ASSESSMENT OF CIVIL INFRASTRUCTURES

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Abstract

Civil infrastructures are always subjected to various types of hazard and deterioration. These conditions require systematic efforts to assess the exposure and vulnerability of infrastructure, as well as producing strategic countermeasures to reduce the risks. This paper describes the needs for and concept of advanced sensor technologies for risk assessment of civil infrastructure in Japan. Backgrounds of the infrastructure problems such as natural disasters, difficult environment, limited resource for maintenance, and increasing requirement for safety are discussed. The paper presents a concept of risk assessment, which is defined as a combination of hazard and structural vulnerability assessment. An overview of current practices and research activities toward implementing the concept is described. This includes implementation of structural health monitoring (SHM) systems for environment and natural disaster prevention, improving efficiency of stock management, and structural failure prevention.

Keywords: infrastructure maintenance, structural health monitoring in Japan, natural disaster mitigation, advanced sensor technology, hazard monitoring, structural vulnerability monitoring

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1. Introduction

Sustainable economic growth, productivity, and the well-being of a nation heavily depend on the reliability and durability of its civil infrastructure. Factors such as construction defect, structural deterioration, material degradation and aging, harsh environmental condition, changing of and increase in loading, as well as extreme event such as natural disaster may contribute to the failure of civil infrastructure in various degrees, from non-optimal performance to a total breakdown. Owing to direct economic consequence of such incidents, the potential causes should be identified and early warning mechanisms should be provided. In other words, civil infrastructures should be managed and maintained properly.

The needs for efficient and effective infrastructure maintenance have obtained strong attentions in Japan recently. These are due to several factors such as the imminent risk of natural disaster, accumulation of aging infrastructures, increasing public demand on high quality of infrastructure, declining government investment in new infrastructure, and the limited expenditure on maintenance. Current practice of infrastructure maintenance in the form of manual inspection still requires massive workforce and is often found unreliable, subjective, tedious, and time-consuming. In recent years, however, innovations have led to the development of sophisticated monitoring 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 an advanced system, large amount of infrastructure can be maintained more effectively and the risk of structural failures can be minimized.

This paper describes the needs for and concept of advanced sensor technologies for assessment of civil infrastructures in Japan. In the beginning, comprehensive backgrounds on problems faced by Japan infrastructure are presented. Following that, a concept of structural assessment by means of risk monitoring and the roles of SHM as an instrument to quantify, evaluate and reduce the risks are described. The paper then describes the possible benefits of advanced sensor technologies in monitoring and presents an overview of monitoring systems in Japan. This overview includes the systems that are still on the research and development stage, and the ones that are already implemented. Finally, future directions and conclusions are summarized.

2. Infrastructure problems in Japan

Constructions of modern civil infrastructure in Japan started during Meiji Era (1868-1912). Investment in railway network was considered a high priority in those days. The present railway network was nearly established in 1940s. Meanwhile, the construction of road network was rather slowly developed and only started before the early 1940s. The first high-speed train (Shinkansen) railway line and the first highway were started in the middle of 1960s. Although the construction of the Shinkansen railway network is not yet fully completed, the total length of the railway has now been considered sufficient.

Majority of investment in development of civil infrastructures in Japan are provided by government. This is evident by the extremely high ratio of government investment to the GDP compared to that of other developed countries in Europe and North America. Investments in new infrastructures, however, are expected to decline in the future. On contrary, maintenance, renovation and rehabilitation of existing infrastructures have become an important issue. The focus of Japanese infrastructure is now shifted on infrastructure maintenance and management to ensure a sustainable infrastructure system. The problems and challenges faced in infrastructure maintenance and management are described in the following sections.

2.1. Infrastructure loss due to natural disasters: Japan's experience

In a report by the Japan Ministry of Land, Infrastructure and Transport (MLIT 2005), several factors were identified as the threats to the sustainable infrastructure. On the top of the list was natural disaster. Indeed, Japan has suffered tremendous loss in terms of properties and human casualties as a result of natural disasters. From 1970 to 2004, for instance, the total loss is approximately US$ 165 billion. Japan shares 15% of the world's total infrastructure losses caused by natural disasters (Fig. 1.a). Earthquakes (76%) and wind storms (typhoons – 22%) are the two major natural disasters in Japan. In fact, Japan accounted for 22.2% of all earthquakes of magnitude 6.0 or larger that occurred in the world from 1995 to 2004 (Japan MLIT 2005). In 1995, Kobe earthquake alone killed more than 6000 people and heavily damaged major infrastructure system. Financial loss was estimated at around US$ 131.5 billion.

In order to mitigate natural disasters and their related casualties, Japan has allocated large amount of resources for activities and research on disaster prevention, mitigation, and recovery. In average, Japan spend around US$ 2.5 to 3.5 billion annually for such activities. This investment has proven to be effective in increasing human safety during natural disasters as evident in Fig. 1.b., which shows that in the past few decades the property loss generally increases, while the human loss significantly decreases.

2.2. Infrastructure stock: condition and management challenges

The peak of infrastructure development in Japan took place between 1955 and 1975. During this period, rapid economy growth accelerated government spending on infrastructure and as a result Japan's infrastructure stocks have accumulated significantly. For transportation infrastructure system, there are approximately 650,000 bridges with the total length of 1,150,000 km constructed in a 370,000-square kilometer of country area by the end of 1950s (MLIT 2005). Now, more that fifty years after constructed, large number of this stock are approaching the end of their service life. Some have aged and deteriorated. In addition, the rush to expand infrastructure during the rapid economy growth had 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. Awareness of the current condition 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 Interstate 35 West Bridge in Minnesota, United States in August 2007 has only intensified the concern considering the 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.

Fig. 2.a. shows comparison of construction years between Japan and United States bridges (Fujino and Abe 2007). It can be seen that in average, bridges in Japan are ten years younger than that of the United States, but greater part of them were built during the same period of time (i.e. 1970s). This means a simultaneous deterioration of large portion of the stock may be expected in near future. In fact, it is anticipated that the number of aged bridges will constitute half of all road bridges by the year 2025. The problem is worsened by the drastic increase in traffic. Daily traffic volume in major highways has increased to as large as 15,000 vehicles per lane, in which the ratio of heavy trucks is also high –in some case it is as high as 30% (Fujino 2005). The high intensity and high frequency loading generated by this high traffic volume creates many problems in bridges. The most typical problem is the fatigue damage on concrete slabs and steel girders.

The importance of maintenance especially at early stages, however, is not equally recognized by local governments and infrastructure authorities. This can be noted from insufficient budget allocation to infrastructure maintenance. Fig.2.b. shows the proportion of local governments' expenditure for infrastructure maintenance –-in this case bridge, as a ratio to the total assets. One can see that many local governments spend less than 1%, or even less than 0.5% of the total assets. The decrease in maintenance expenditure is expected to continue in the following years due to budget constraints.

The abovementioned explanation highlights two characteristics of infrastructure problem in Japan. One is the increase in volume of maintenance work due to the increase in the number of aging infrastructure, continuous threats of natural disasters, and higher expectations on standard of life and public service. The other one is the decrease in maintenance budget and the possible shortages of workers. The use of advanced technology in the framework of SHM is currently attracting wide interest as one of the key solutions to these two problems.

3. SHM and risk management

3.1. Concept of risk management of civil infrastructure

The idea of SHM can be viewed in a general framework of risk management. It is not only an engineering issue, but also requires social and economic interaction. In this context the owner of an infrastructure (i.e. central or local government or private sector) is primarily concerned with the well-being of their assets. The question is then how can the asset be maintained so that it remains productive throughout its service time. To answer this question the owner is confronted with a problem of risk management. In this viewpoint the risk of infrastructure failure is defined as a product of hazard and vulnerability, in the form of:

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

Hazard describes the probability of occurrence of unexpected events that may endanger the structure, such as natural disaster, while structural vulnerability refers to the susceptibility of the structure when subjected to hazard.

In managing the risk, there are three steps involved, that is risk assessment, risk quantification and decision making (Fig.3). In the first step we assess the risk by identifying and understanding the nature of hazard and vulnerability of structure. Hazard is defined as the probability of occurrence of certain level of unexpected event at one location in a certain time. Therefore it is a spatial and temporal dependent. One approach to evaluate hazard is by using a hazard map that estimates the relative hazards considering both severity and the frequency of occurrence. An example of hazard map is the seismic hazard map that quantifies the seismic intensity of a particular area using the probability of exceedance (Cornell 1968). The methodologies for performing hazard analysis have been well developed, and have become common practices.

Equally important with hazard assessment is the vulnerability assessment. This part is the domain of SHM. Conventional practice assumes that structural vulnerability is time-invariant, in that it is only 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 a temporal dependent in that it may differ from time to time due to deterioration, aging, or changing in environmental and loading conditions. For these reasons, field monitoring of the structure condition may be the only feasible option to asses the time variability of the structural vulnerability.

The second step in risk management involves quantification of the risk. At this step, the information obtained from hazard and vulnerability monitoring is processed and quantified into the potential or actual risk. The last step is decision making. At this point, a decision maker is faced with three possible options: 1) to accept as it is, 2) to reduce and 3) to mitigate the risk. When the level of risk is considered acceptable, no further action is required. However, when the risk is considerably high, risk reduction and mitigation option are selected to reduce the potential damage in a form of repair and retrofit work.

3.2. The role of advanced sensor technologies in risk management

We can view the risk management as a bottom-up process where the quality of decision made at the end of the process is highly dependent on the accuracy and reliability of information provided by the first two steps. While decision making is a managerial domain, the first two steps constitute major engineering involvement where technologies play a vital role. The technology we refer to here is the hazard and vulnerability monitoring technologies. The methodology and technology for hazard monitoring have been developed relatively earlier than for vulnerability monitoring. Some of them are now well established and have become common practice such as seismic hazard and typhoon hazard map. Vulnerability assessment technologies, or more commonly called SHM technologies, however, are still developing. They include *instrumentation or sensing technology*, *signal processing* and *structural assessment technology*.

From engineering viewpoint, implementation of SHM technologies in risk assessment have at least two benefits: 1) increasing the quality of information by reducing the uncertainties associated with measurement, and 2) allowing measurement and assessment of more structures at a shorter time; or in short, improving the quality and efficiency of risk assessment. Deployment of SHM technologies is also important for infrastructure owner to: 1) assist the decision making, 2) reduce the manual maintenance cost, 3) prevent a sudden failure of infrastructure and the liability claim that may follow, and 4) facilitate an optimal use of maintenance budget by prioritizing the use of budget to the more critical structure.

Obviously there is a cost-benefit tradeoff of deploying an SHM technology. From engineering perspective a more advanced technology will most likely result in a more accurate assessment. However, it comes with a price that should be treated carefully so that the overall benefit still exceeds the investment in technology. It should also be noted that the benefits of investment in technologies for infrastructure maintenance may not come immediately. A recent study (Fujino and Abe 2007) shows that when the Japan Railways (JR) invested in the disaster prevention and maintenance programs, the performance of railway system improved significantly and the number of train accidents decline. These results, however, were achieved after a certain period of time, as shown by the cross-correlation between the investment and the number of accidents (Fig 4). The negative correlation in this figure indicates that the number of accidents may not decline unless accident prevention investments are made. The rather flat correlation suggests that effects of disaster prevention investments are not immediately materialized. On the contrary, the benefits of similar investment made in engineering plants become visible more immediately, but do not last for long time. This goes to show that negative impacts may not come immediately even if we do not invest in any preventive measures.

However, in the long run, we may suffer from greater consequences. These results emphasize the slow impact of investment in the SHM and disaster prevention of infrastructure, and the long term management strategy it requires.

4. Development in SHM technologies

There are two main branches of research and development in SHM, 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 may represent structural condition in form of performance indicators. Extensive developments and innovations have been made in recent years in both branches. This section describes briefly some critical issues in development of SHM technologies.

4.1. Developments in advanced sensing technology

Many research efforts in developing an advanced sensor system for SHM have been reported in literature. One may observe a converging trend in sensor development toward a new type of sensor that is small, smart, wireless, and self-sufficient in power consumption. This would replace the current portable sensors that are linked with cables and required centralized operation as well as power consumption system.

A smart sensor has data processing capability in it. It can locally process measured data and transmit only the important information through wireless communication. When a monitoring system requires many sensors, wireless communication appears to be attractive. The high cost associated with the installation of wired sensors can be greatly reduced by employing wireless sensors. Digital conversion on the wireless sensor node also eliminates possible signal degradation during analog signal communication through long cables. Example of development of smart sensor is reported by (Nagayama et. al 2007). A comprehensive review of smart sensor technologies and their adoption in structural health monitoring has been reported (Spencer et.al. 2004).

There are also notable developments of high-performance sensor technology in Japan using the optical fiber sensor (OFS) technology. Using an optical time-domain reflector (OTDR) technique such as Brillouin Optical Time Domain Deflectometry (BOTDR), the distributed optic fiber sensing technique provides information on strain distribution along the optic fiber in terms of value and location that can be used to monitor the performance of structural members such as reinforced concrete and detect the crack initiation as well as crack's width. Examples of such applied sensor system have been reported in (Mita 2000 and Wu 2003).

When choosing sensor for monitoring civil infrastructure there are two aspects need to be considered:

1) The size of monitored object and scalability of the sensor. The selection of sensor is determined by the size of the monitored object. When it comes to a large scale object such as the global scale, global sensors linked to satellite in the global positioning system (GPS) are used. On the other hand, for the micro scale object, the sophisticated nano or micro sensors are more suitable. The civil structures can be considered between these two extremes, hence the meso scale. They have many components with many variations so that in order to monitor the local and global condition, the use of a too-expensive and sophisticated micro-sensing system can be prohibitively expensive. To effectively monitor a large civil infrastructure, a set of dense array sensor is needed. Such a dense array must be designed to be scalable, which means that the quality of information conveyed and the system performance do not degrade substantially as the number of components increases.

2) Durability. Many important civil infrastructures are built in severe environment. They are designed to last for long time, typically over 50 years. During service life, hazardous events may not occur very frequently, but nevertheless the monitoring system must be always reliable over the lifetime of the structure. Therefore sensor type, lifespan, and

packaging/embedding durability considerations are important aspect in selecting the sensor and monitoring system.

4.2. Structural diagnostic/prognostic

On the structural diagnostic/prognostic, the methodologies can be categorized according to the scope and the 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 global structural integrity and its evolution are the monitoring objectives. 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 SHM and existing inspection methodology.

Type of analysis deals with the way the problem is solved. This is arguably the most crucial ingredient of a structural diagnostic process. The type of analysis can be broadly divided into two, according to the usage of model in analysis, as: 1) an inverse problem, and 2) a pattern recognition problem. The first approach usually adopts a model of the structure and tries to relate changes in measured data from the structure with the changes in the model by employing an inverse problem, sometimes locally linearized ones. Excellent survey of the dominant methods on this category can be found in Doebling *et al* (1996). The second is a model-free approach, which is based on the idea that the measured data from the system of interest are assigned to a damage class by pattern recognition algorithms (Worden 1997, Worden et.al. 2002).

Regardless of technologies and methodologies selected for monitoring system, there are four aspects that one should clearly understand before conducting monitoring:

1. A clear objective of monitoring. Monitoring system can have several objectives such as: structural observation during extreme events, failure prevention, damage detection, and stock management. Once the objective is defined one can select a set of structural

features as indicators of the structural conditions that fit into the objective of monitoring. Following that, the appropriate sensors that can best capture these structural features are selected.

2. A complete understanding of sensor capabilities and limitations. Sensors should be able to perform the intended functions during the designated monitoring time. Sensitivity, durability, range of measurement, and limitations of the sensor and data acquisition devices should be clearly understood.
3. A clear and quantitative definition of the choice of the feature used as indicator of the structural condition. Since sensor cannot detect damage directly, feature(s) are extracted from measurement through signal processing and structural identification. These feature e.g. modal parameters, strain, etc, convert sensor data into damage information. Therefore, it is important that the features represent the actual condition of the structural. They should be sensitive enough to detect damage at earliest stage possible, and at the same time not too sensitive to the non-damage quantities.
4. Cost-benefit analysis of the monitoring system. Once the objective of monitoring and sensor system are selected, the costs associated with developing, installing, operating and maintaining the SHM system should be evaluated and compared with the benefit of the system itself in near-term and long-term. It is important that the overall benefits of SHM system outweigh the total cost associated with its implementation.

5. Examples of monitoring system for risk assessment of civil infrastructures in Japan

As mentioned in section 3, a comprehensive risk monitoring of infrastructure can be achieved by a combination of hazard and vulnerability monitoring. This section presents some examples of the two types of monitoring systems in Japan. Certainly, these examples do not do justice to years of research and development in hazard and vulnerable (SHM) monitoring system in

Japan. However, they may represent the current research and development activities in this field.

5.1. Hazard monitoring

Learning the lessons from previous natural disasters, Japan has now developed comprehensive hazard monitoring systems on a national scale. The systems have proved to be effective in assessing and communicating the risk and also facilitating decision making. Brief explanations of several high-profile systems are listed below.

1. Kyoshin-Net (K-NET). A comprehensive seismic hazard monitoring system was developed after the 1995 Kobe earthquake. The system constitutes a network of 1034 wideband seismographs installed at the ground surface nationwide (Kinoshita 1998). In addition to K-NET, there is also a network of highly sensitive seismographs, called Hi-Net, consisting of 679 stations, of which 659 stations are equipped with seismographs at ground and depth surface (KiK-NET) (Okada et.al 2004).
2. AMeDAS. A high-resolution surface monitoring system involving wind, temperature and other meteorological data was developed by Japan Meteorological Agency (JMA). The Automated Meteorological Data Acquisition System (AMeDAS) consists of about 1,300 stations with automatic observation equipment. These stations, of which more than 1,100 are unmanned, are located at an average interval of 17 km throughout Japan and already in place starting from 1974 (JMA-AMeDAS).
3. SUPREME. Recently, as a part of a seismic disaster prevention system, Tokyo Gas has installed a real time monitoring system named Super Dense Real-Time Monitoring of Earthquakes (SUPREME) that consists of 3800 transducer of spectrum intensity sensors, 20 liquefaction sensors to monitor subsurface pore water pressure, and 5 seismographs. The system evaluates intensity of ground motion and stops the distribution of gas when

a certain level of earthquake occurs. Installation of the upgraded sensor network was completed in March 2006 and the system is now in place (Shimizu *et.al.* 2006).

4. TERRA-S. Shinkansen also has a seismic disaster prevention system. The Tokaido Shinkansen Earthquake Rapid Alarm System (TERRA-S) detects the arrival P-wave from K-Net stations in close proximity and determines the impact of the seismic wave to the Shinkansen and railway infrastructure. When the level of ground motion is considered critical to Shinkansen operation, an alarm is immediately sent to the running train. Power transmission from substations to the Shinkansen trains is automatically suspended, before the more destructive S-wave reaches the regions on the Shinkansen routes. Recently, the system has been upgraded and the new installation cost around US$ 6.3 million (JR Central 2005).

The SUPREME and TERRA-S systems, in particular, are excellent examples of real time hazard monitoring systems. In application of the TERRA-S for instance, once the train stops, visual inspection is conducted to ensure that the railway and the supporting structures are safe. This inspection, however, may take from few to several hours and depends heavily on human labors. After performing such inspections, train operation resumes when the structure condition is considered safe.

5.2. Structural vulnerability monitoring

The authors and their associates have been involved in developing several monitoring systems for structural vulnerability assessments. Status and progress have been reported in a number of papers. The objectives of monitoring systems are three-fold: environment and disaster prevention, stock management, and failure prevention.

5.2.1. Structural monitoring for environment and disaster prevention

5.2.1.1. Earthquake

Because of the high intensity of seismic activities in Japan, monitoring for seismic response has been widely employed for decades. The objectives of the monitoring system are to evaluate seismic performance, verification and comparison with seismic design, observation of possible damage and prevention of failure. Particular attentions are given to the 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).

One of such examples is the dense monitoring system installed on Yokohama-Bay Bridge (Fig. 5.a) (Siringoringo & Fujino 2006, 2008a). The bridge was constructed on the soft soil that a new special foundation system was needed (The Yokohama Bay Bridge 1991). It is located near an active fault and close to the epicenter of the 1923 Great Kanto Earthquake. These conditions have made seismic performance a major concern. Therefore to confirm the seismic design and to monitoring the bridge performance during earthquake, a comprehensive and dense array monitoring system was installed.

The study shows that seismic performance of the bridge can be evaluated by observing the dynamic characteristics under various levels of earthquake. Structural global performance such as amplitude dependency of damping ratios and variations of mode shapes were observed. For structural local performance, the investigation of the seismic isolation device, i.e. Link Bearing Connection (LBC), is of interest. The LBC is designed to minimize the effects of inertia force of superstructure to substructures by decoupling the modes at the end pier-girder and tower-girder connection. For this purpose, the LBC is expected to function as a longitudinal hinge connection that indicates the girder and pier caps work as separate units.

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 (Fig. 6). The modes 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 taken place. 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, the stiffer connection and higher natural frequency were identified.

These results indicate that performance of LBC depends on the amplitude of earthquake excitation and does not always follow the prediction or design performance. Although the study was focused on comparison with design and analysis, the result implies that an 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.

5.2.1.2. Wind

Nowadays monitoring for wind-induced vibration has also been widely employed especially for long span bridges in Japan. One of such measurement systems was employed on the Hakucho Bridge in Hokkaido (Fig 7) (Nagayama et.al 2005, Siringoringo and Fujino 2008b). The initial objective of the monitoring was to verify the results of wind tunnel test, especially concerning the aerodynamic force. At the time of the test, bridge engineers in Japan were mainly relied on wind tunnel test and there was little effort to confirm the result with a full-scale monitoring of the real bridge. In fact, this was the first initiative in Japan to monitor a long-span bridge with a very dense-array of sensor (i.e. forty measurement points on one half-span of the bridge) for over two weeks.

With such dense-array of sensor and long measurement period, the bridge performance under various levels of wind speed can be observed. The records show a quadratic relationship between wind velocity and vertical deck response. By using system identification (i.e. Eigensystem Realization Algorithm) dynamic characteristics of the bridge was identified. The results show these characteristics (i.e. natural frequency, damping ratio and modal phase angle) vary with respect to wind velocity.

The changes are quantified by employing an inverse structural identification (Nagayama et.al. 2005), where the changes in modal parameters are represented by additional stiffness and damping provided by the bearing friction and aerodynamic force. Results show (Fig. 8) that the aerodynamic stiffness and damping can be identified and are of the same order with the wind tunnel measurements. The changes of dynamics parameters are attributed largely to the friction of bearings located at the tower, which move only when the acceleration of bridge deck exceeds a threshold value (i.e. when root-mean-square of response is higher than 0.2 cm/s^2). The results show that by employing a monitoring system, performance of bridge under various wind condition and its local component can be evaluated.

5.2.2. Structural monitoring for stock management

Monitoring is also expected to improve the conventional inspections and to rationalize stock management by increasing the efficiency, reducing the cost, and improving the accuracy. In this section, three examples of this type of monitoring are briefly discussed: a) a short-span skew bridge; b) a shinkansen viaduct; and c) routine inspections by train and vehicle intelligent monitoring system.

5.2.2.1. Monitoring of a short-span skew bridge

The major portion of bridge stock consists of the short and medium span bridges. They are located mostly in rural areas and subjected to an increasingly heavy traffic load. Due to limitation in land use in Japan, some of them have unsymmetrical or skew girder. Performances of these skew bridges are different from the symmetrical ones due to different load distribution. Japanese bridge design code, however, has not fully addressed this problem so that monitoring of the real bridge performance become increasingly important. Considering the large number of the skew bridge, selecting an appropriate SHM system is essential for an efficient stock management. This includes the selection of appropriate sensors; processing and interpreting the large number of data, and extraction useful information about bridge condition.

The study in (Xia et.al. 2004) demonstrates how to apply some available algorithms to the data measured by an SHM system and how to evaluate the results. In this case a skew bridge is instrumented with vibration transducers, strain sensors and temperature sensor. Dynamic characteristics, temperature effects, stress conditions, and fatigue damage evaluation were studied using the monitored data. Evaluation results revealed some problems that may be early symptoms of structural deficiency. Further special retrofit measure was suggested, even though the bridge itself was relatively new (12 years old). Structural problem is attributed to the stress distribution at the edge of skew girder, which may have not been appropriately treated in design. The results demonstrated the possible benefits SHM system in detecting early signs of deterioration and providing a feedback for improvement of the design code.

5.2.2.2. Monitoring of Shinkansen viaducts by LDV

High-speed train (shinkansen) network is a vital infrastructure system that connects major cities within Japan main islands. The network is supported by reinforced-concrete and steel viaducts, many of which were constructed over 40 years ago. Because of 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 affects the condition of the viaduct and the supporting structures. Some signs of deteriorations especially cracks on the steel viaducts have been reported. These deteriorations are also attributed to the increasing service loads as a result of increasing volume and speed of Shinkansen.

In order to investigate the effect of train speed on the viaduct, a highly sensitive monitoring system that can operate during an instant time of train passing was developed. The system utilized Laser Doppler vibrometer (LDV) and measured the three-dimensional dynamic response of steel viaduct girders (Miyashita et. al. 2007). The viaduct had undergone a retrofit, to strengthen the deck after vertical cracks appeared on the welded portion of stiffener of the lower flange. By recording local responses of this portion during various train speeds and converting the measurement results to the stress distribution, it was confirmed that this crack was due to the stress alterations caused by the various train speeds. Therefore the retrofit programs must take this factor in to account.

Another important aspect is the evaluation of viaducts columns. Viaduct columns are inspected regularly or after occurrence of an earthquake. For this purpose, the structures are excited by impact hammer and the responses at several locations on the columns are measured. Considering the number of viaducts, this technique is obviously time-consuming and requires massive manpower. In the study by (Hernandez et.al. 2006), an automatic non-contact inspection system using LDV is proposed (Fig. 10). The method utilizes ambient vibration measurement and applying system identification to identify modal parameters of the viaducts. Afterward, the local modes associated with viaduct columns are analyzed and compared with the modes derived by FEM. By employing the modal strain energy method, the condition of columns and the connection with substructures are evaluated. This method requires availability of an FEM at the beginning as a baseline for comparison. In the future, however, one can use the model to evaluate columns condition at each monitoring process. Further development and improvements of this system are expected.

5.2.2.3. Vehicle based intelligent monitoring systems

Maintenance of railway track and highway pavement is important for safety. However, due to limited maintenance budget not all local railway and highway operators can apply a sophisticated and costly maintenance strategy such as the one employed by the major railway and highway operators (i.e Japan Railway or Shinkansen). Instead, they rely on manual track/road profiler, whose accuracy and efficiency are often inadequate.

To provide a simple, low cost with sufficient accuracy railway track monitoring system, the Train Intelligent Monitoring System (TIMS) was developed (Ishii et.al., 2006). The objective of TIMS is to detect railway track irregularity using vibration technique. The system is installed on a train and responses are recorded and analyzed regularly. The system consists of: 1) a triaxal accelerometer(s) mounted on floor of train, 2) a Global Positioning System (GPS) sensor and, 3) a portable computer to record position and response data (Fig. 11). By looking at the root mean square (RMS) of the acceleration responses, one can evaluate the response characteristics while the GPS sensor provides information on location. With repetitive measurements, equal response characteristics are expected. The distinct change on the response may then be attributed to the change in railway surface or to a settlement of the track bed.

Using this monitoring system one can identify the locations of deterioration on a railway surface or on a track bed to direct an efficient repair work. The facts that the system is portable and compact make it suitable for application on an ordinary train with relatively low cost. The system had been applied to a local railway in Chiba prefecture. Promising preliminary results were obtained. Further development of the system is still under ongoing research and improvements are expected.

A similar monitoring system was developed for highway. The Vehicle Intelligent Monitoring System (VIMS) (Fujino 2005) utilizes dynamic response of an instrumented car to capture the condition of road pavements surface as well as the condition expansion joints. The VIMS system consists of: 1) a car with known dynamics properties, 2) an accelerometer to measure the dynamic response of the car, 3) a GPS sensor to identify the position where the dynamic response is recorded, and 4) a portable computer to store the measurement data (Fig. 12). Pavement condition is evaluated by employing the International Roughness Index (IRI) (Sayers 1995). For this purpose, the acceleration records measured by VIMS are converted to that of a standard quarter car model, as required in the IRI, by employing a transform function.

The IRI index quantifies the roughness condition at each measurement, and by continuous measurement the condition of highway pavement can be closely monitored.

Furthermore, one can determine the location of expansion joints on a highway bridge by comparing the amplitude of dynamic response and analyzing the peaks in frequency spectrum that associated with vehicle natural frequencies. The deterioration of expansion joint would create an uneven surface that would be recognizable from frequency analysis of acceleration response. This system has been tested by the Tokyo Metropolitan Expressway, and its effectiveness to the road maintenance, i.e., frequent monitoring of the conditions of road pavement and expansion joints, has been confirmed. The system is simple and effective in reducing the operational cost as compared to the conventional monitoring system that uses a road profiler.

5.2.3. Structural monitoring for failure prevention

Monitoring is also expected to prevent structural failure at a catastrophic level by providing an alarm of structural failure at earlier stage. This is the objective of monitoring for failure prevention. For this purpose, it is important that the failure mode is identified or specified so that a monitoring system can be implemented locally to observe that mode of interest. Several such monitoring systems have been developed and implemented for safety of railway operation. Fig. 13.a shows an example of monitoring system to monitor unseating of a bridge girder. The system works in such a way that when unseating occurs, the sensor breaks and a signal is sent to railway operator to suspend train operation. The system is also installed to overpass bridges above highway where collision risk is considerably high. Another example is the scour monitoring. Fig 13.b shows clinometers installed at bridges to detect scour-induced collapse of bridge piers (Suzuki et. al. 2007). Alarm is sent when the inclination reaches the limits, and further inspection is conducted to prevent structural collapse.

6. Future Directions: shifting paradigm and benchmarking

We expect future developments in technology and methodology that will include multi-disciplinary research efforts encompassing fields such as sensing devices, smart materials, structural dynamics, signal processing, computational hardware, data telemetry, statistical pattern recognition and many others. We also expect new implementations on more complex structures and deterioration problems in the future.

With advancement in technology, the size and cost of a sensor is expected to decline in the future. Computational cost is also expected to decline as the more powerful computers are now readily available. Communication between sensors for a large scale measurement becomes more effective with application of wireless system. With these conditions, there is a trend of installing many sensors in one structure to improve the quality of assessment. On the other hand, it may be also interesting from research point of view to put only few sensors but on many typical structures. With this approach, we can study the response typical structures, create a database for structural assessment, and define a quantitative measure as performance indicator of that typical structure for a certain level of hazard. Such a database will be important for improvement of our understanding and development of design code. This may be one possible future direction in a practical application of SHM.

Realizing the needs for health monitoring technologies, the Japanese government started national projects that involve many industries and universities. Under the scheme of university-industry collaboration projects sponsored by the Ministry of Economy Trade and Industry, several research projects that include structural health monitoring, smart manufacturing, adaptive structure and materials were started in 1998 (Mita 2000). This government-university-industry collaborative program, although still emphasizing a leadership of universities researchers, is expected to foster the public-private partnership as a driving force behind the SHM and in infrastructure maintenance in the future.

In the past few years, we have seen many projects that implement SHM systems to major infrastructure such as bridges in Hong Kong (Wong 2004), and the Bill Emerson Memorial Bridge (Celebi et.al. 2006) to name a few. Unfortunately, we have also seen structural failure even when a monitoring scheme had been implemented (the recent Minnesota Bridge collapse serves as a good example). Consequently, many are still skeptical about the usefulness of SHM. The high costs of these projects should therefore be justified with the results. It is our responsibility to convince that SHM is not only fashionable but also essential for our structures, and that all infrastructure' stake-holders gain benefit from the monitoring. In other words, SHM should move from the *nice-to-have* paradigm to the *need-to-have* one.

Although many SHM systems are currently being implemented, authors find they are mostly applied with different techniques, to different structures, under various conditions. Consequently, there is no general understanding of the results. In authors' opinion, it would be beneficial if the efficacy of various structural health monitoring methods are studied using a real benchmark problem. The ASCE-SHM benchmark problem (Dyke et.al 2003) and the Z-24 Bridge (Peeters and DeRoeck 2000) are excellent examples of such initiatives. Both problems have attracted interest from many researchers worldwide and contributed significantly to the advancement of the SHM field. In the future, initiatives to provide a realistic and comprehensive benchmark monitoring system on a real structure and to disseminate the monitoring information should be encouraged.

7. Concluding Remarks

The needs for and concept of advanced sensor technologies for risk assessment of civil infrastructure are described with special attention given to the Japan civil infrastructures. The problems faced by Japan in realizing sustainable infrastructure system are mainly due to: (1) environment and natural disasters, (2) deterioration of large portion of its infrastructure stock, while at the same time there is increasing public demand on not only safe but also high quality of infrastructure. The paper shows that an accurate risk assessment relies not only on hazard monitoring, but also on an accurate vulnerability monitoring. This latter aspect can be achieved by implementing a comprehensive SHM system, in which the implementation of advanced sensing technology plays an important role.

The trends in sensor technologies and monitoring methodologies are discussed, as well as the justification and the principle in selecting the SHM system. Two types of monitoring systems in Japan that is hazard and vulnerability monitoring are described. It is realized that while hazard monitoring systems are very advanced and well-established, vulnerability monitoring systems are still somehow lag behind. Examples of vulnerability monitoring in the form of SHM of infrastructure such as bridges are explained in this paper.

Monitoring of loading, environment effect, and structural integrity during extreme events such as earthquake and wind storm have been the primary objective of early initiatives of SHM systems. Recently, SHM systems are also being developed to improve efficiency of stock management. The paper also highlights two aspects for future directions of monitoring. They are the paradigm shift of SHM from *fashionable* to *essential,* and the importance of a real structural benchmark problem.

8. Acknowledgements

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Figure 1 (a) Natural disaster damage cost ratio by regions, and (b) Number of loss and casualties caused by natural disasters in Japan.

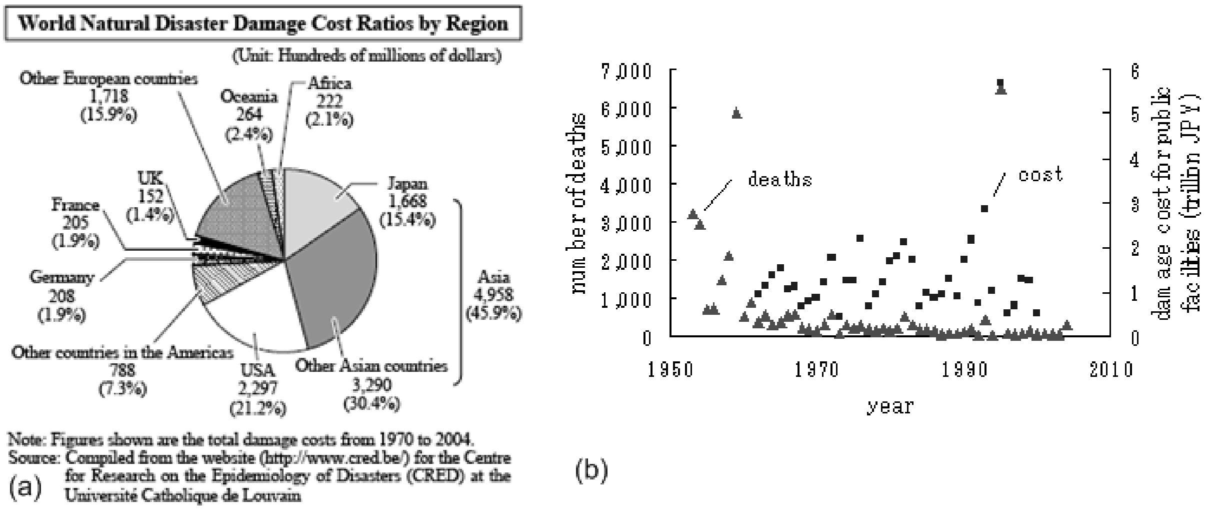

Figure 2 (a) Comparison of bridge construction period between Japan and US, (b) Local government expenditure for infrastructure maintenance

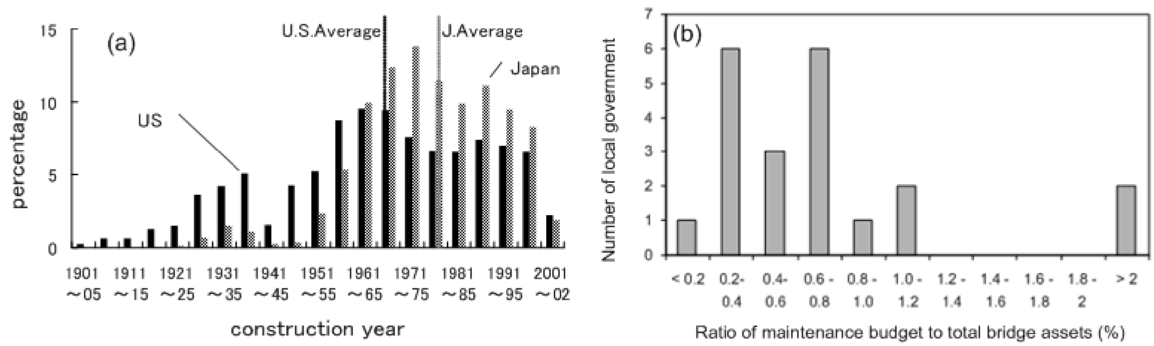

Figure 3. Schematic figure of risk management of civil infrastructure involving SHM

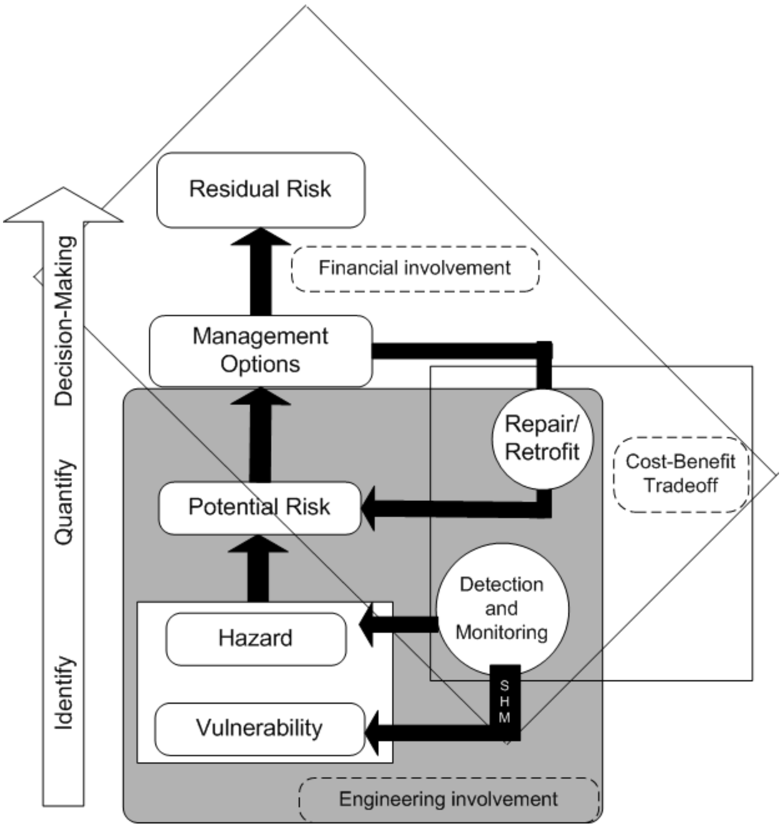

Figure 4 (a). Comparison between the number of accidents and the number of disaster prevention investment made by Japan Railway (JR), (b). Cross-correlation between number of investment and number of train accidents.

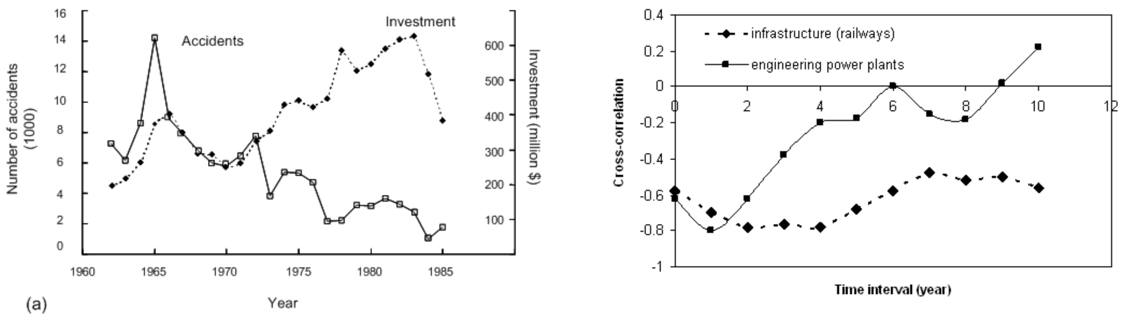

Figure 5(a) Yokohama-Bay Bridge (b) Vibration sensor network of accelerometers.

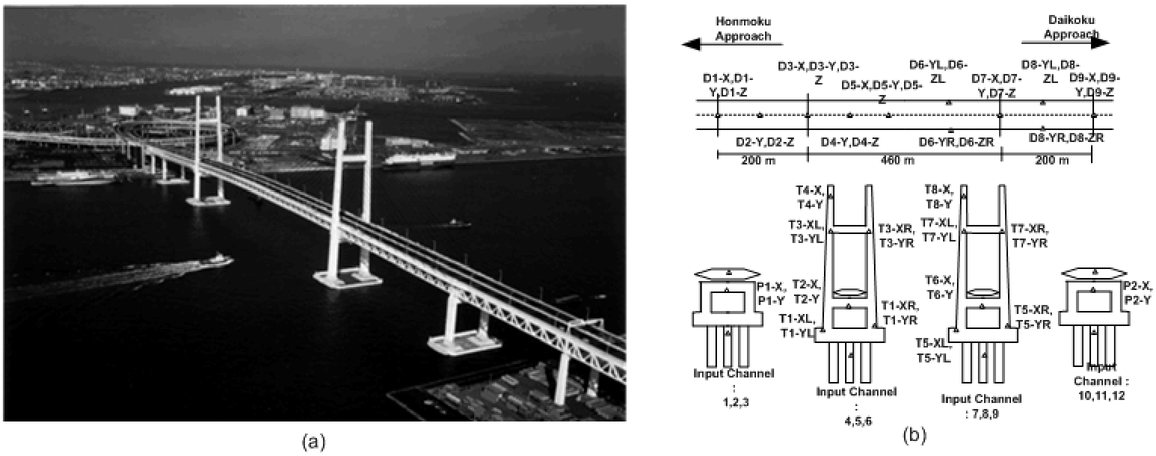

Figure 6. Two typical first-mode of Yokohama-Bay Bridge identified from seismic records (a) hinged-hinged mode (b) fixed-fixed mode

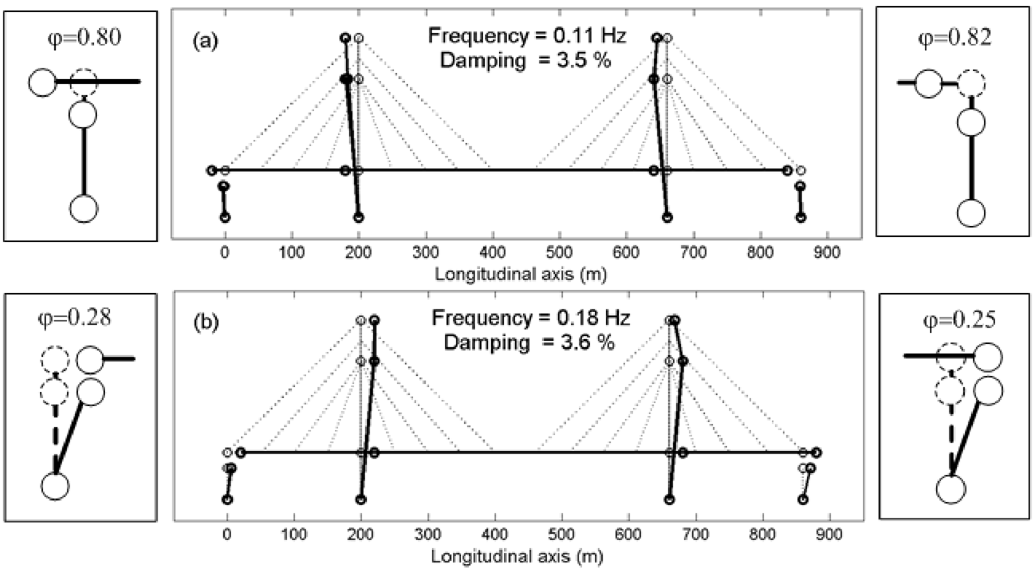

Figure 7. View of Hakucho Suspension Bridge, sensor position and measuring direction.

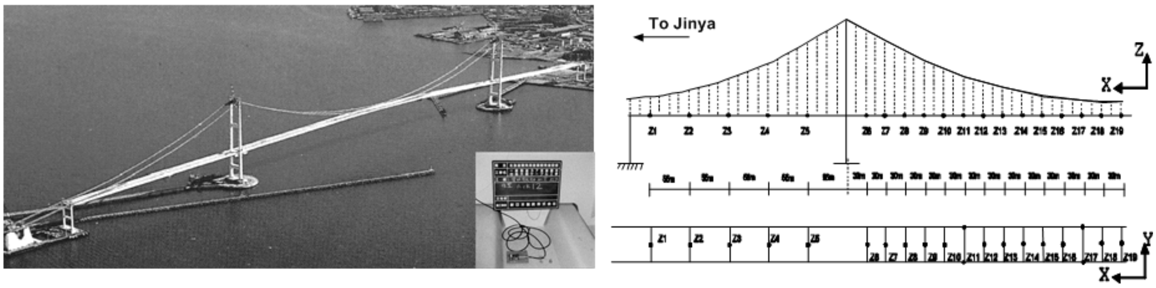

Figure 8. Identified changes in (a) aerodynamic damping, (b) aerodynamic stiffness, (c) bearing friction damping, (d) bearing friction stiffness of the Hakucho Suspension Bridge

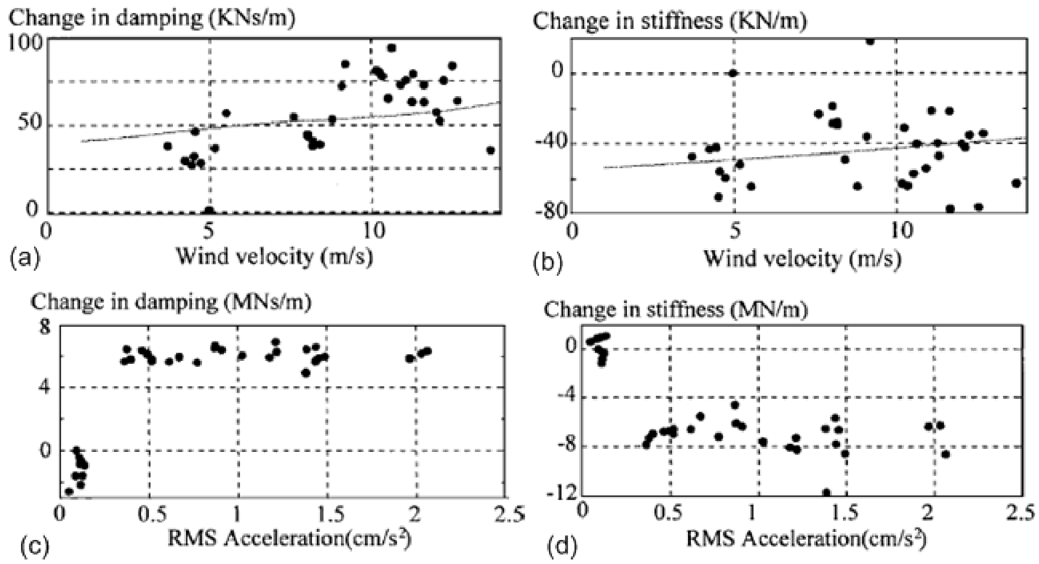

Figure 9. Skew bridge near Tokyo and its monitoring system

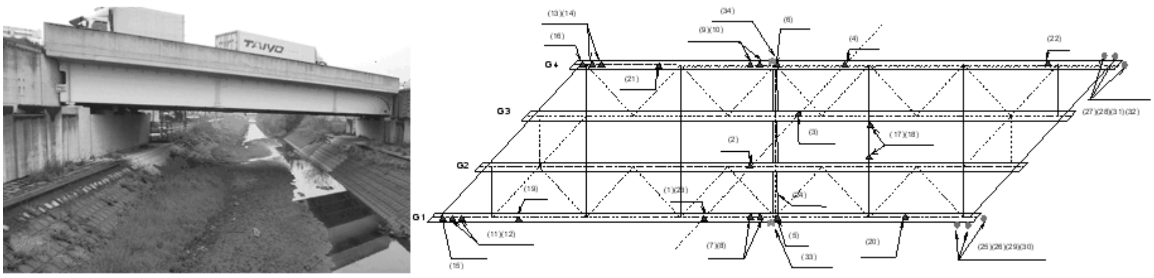

Figure 10. Shinkansen viaduct monitoring system using ambient vibration and Laser Doppler Vibrometer

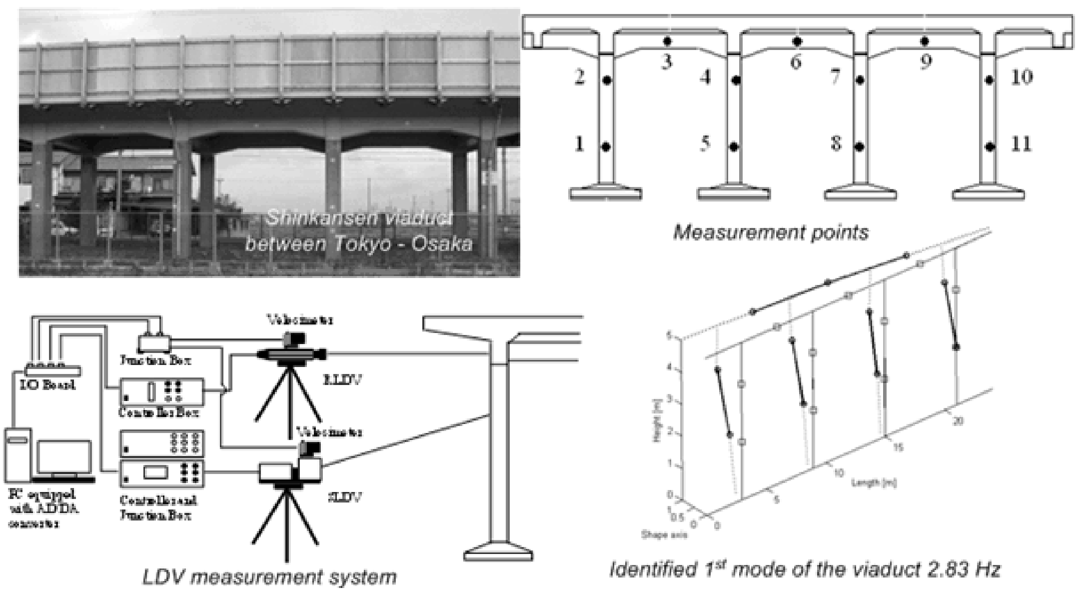

Figure 11. Train Intelligent Monitoring System (TIMS)

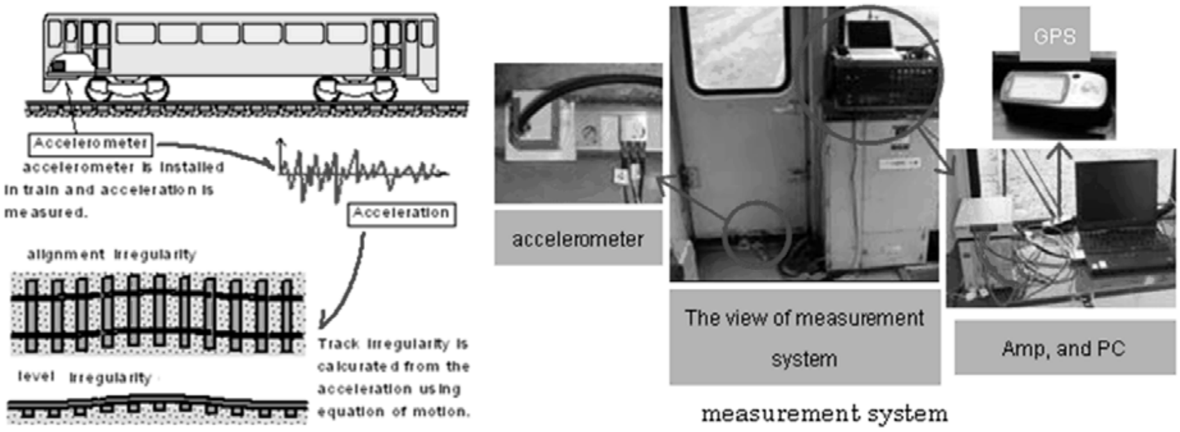

Figure 12. Vehicle Intelligent Monitoring System (VIMS)

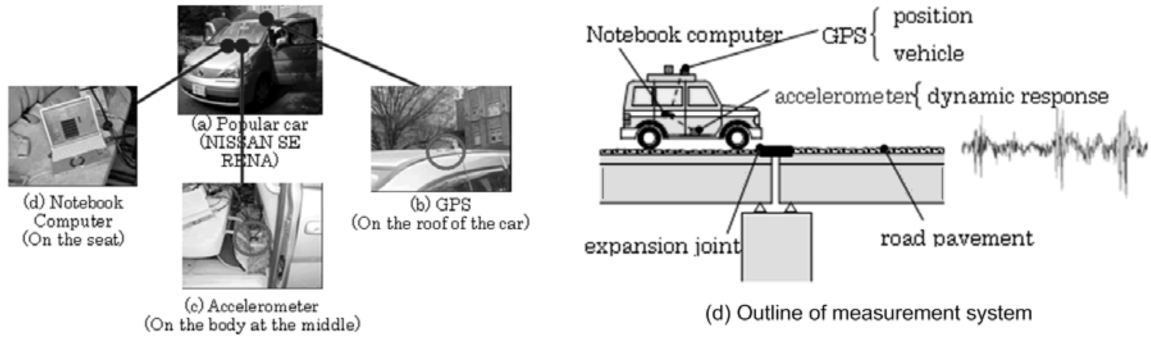

Figure 13. a) Bridge unseating sensor, (b) Clinometric type bridge scouring sensor (After Suzuki et.al. 2007)


(a)


(b)