Intelligent Sensory Technology for Health Monitoring Based Maintenance of Infrastructures

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ABSTRACT

In order to maintain sustainability of infrastructures in which have significant influence to social lifelines, an economical and rational maintenance management system is absolutely needed. Maintenance management of infrastructures and reduction of their life cycle cost (LCC), become serious problems those have to be solved urgently. In this paper, Structural health monitoring based maintenance (SHMBM) aimed to reduce structure's life cycle cost is proposed. Theoretical background of SHMBM and contribution of monitoring information in LCC reduction are reviewed. As the tools to retrieve the structural deformational properties information, the intelligent sensory principles and their sensory system are introduced such as GPS based MMS monitoring technology, peak memory sensory technology, elasto-magnetic sensory technology and fiber optical sensory technology. Their reliabilities were verified by some verification test and field application test. Some examples of SHMBM application in the monitoring of structural properties are also described as well.

Keywords: SHMBM, LCC, GPS-based MMS, EM sensor, Peak sensor, Fiber Optic sensor

1. INTRODUCTION

The civil engineering infrastructures in Japan were getting their ripeness at the end of 20th century and in the near future it is estimated that new construction investment will be reducing while maintenance and reconstruction costs of existing structures will be increasing rapidly as shown in Fig.1[10,11].

Deterioration mechanisms of structure due to numerous loading condition and various un-anticipated loads have highly complexity. The most deteriorated factor does not due to catastrophic event such as seismic and typhoon, but due to nature phenomenon such as aging, weather, fatigue, overload and structural settlement as show in Fig. 2[14,16]. These all factors which are hidden inside 'the black box' contribute to the long-term degradation of civil infrastructures. A reliable SHMS should be derived to monitor the effect of these parameters on the integrity of such structures as distortion, deformation, stress change, crack propagation and corrosion progression[27]. Long-term monitoring on structural deformational response will indicate structural degradation as a warning paradigm before catastrophic failure.

As the basic concept in developing new innovative sensory methodologies, it is considered that an intelligent monitoring system should be supported by sensor which fulfill "$A_{to}E$" characteristic as: (A)ccuracy: sensor should have a reliable accuracy; (B)enefit: commercial price of the sensor should be reasonable; (C)ompendiousness: sensor size should small enough, especially for embedded type, no local failure occurrence should be guaranteed; (D)urability: serviceability of the sensor should be durable and long-lived; and (E)ase in operation: sensor should be easy to operate and time consumed for measurement should be close to real time measurement[1,18,24].

SHMBM is the basic engineering effort to collect maintenance information, forming a database system to open to the public or citizens for making decision on a suitable solution strategy to extend structure's life. Sustainability of the infrastructure structural performance and health can be assessed based on the structural information recorded from a reliable continuous structural health monitoring system[6].

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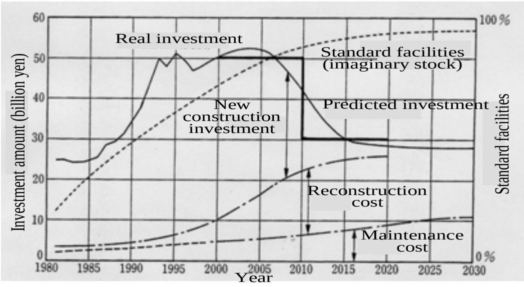

Fig.1. Infrastructure investment phenomena

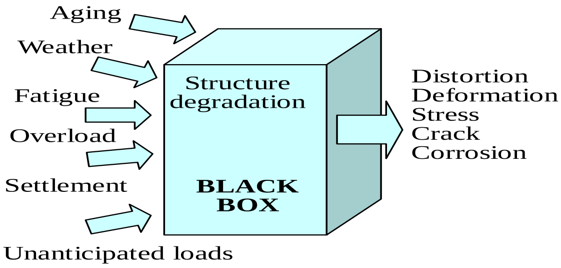

Fig.2. SHMBM as tell-tale of structural degradation phenomena

2. STRUCTURAL HEALTH MONITORING BASED MAINTENANCE

2.1 Philosophy

As the basic technology to collect maintenance information, SHMBM forms a database system to open to the public or citizens for making decision on a suitable solution strategy to extend structure's life. In practicing this concept, citizens are not just as users but also as the owners of an infrastructure. One of the efforts is the engineering development of infrastructure life cycle management as shown in Fig.3. During the lifetime of a structure, the expected total cost C_T was proposed by Frangopol that can be expressed mathematically as follows[8].

$$C_T = C_I + C_{MAI} + C_{INS} + C_{REP} + C_D \tag{1}$$

C_I is the initial cost of the structure, C_{MAI} is the expected cost of maintenance, C_{INS} is the expected cost of performing inspection, C_{REP} is the cost of repair, C_D is the cost of demolition. In this approach, the cost of performing inspection and the cost of repair are considered as cost of maintenance. This conceptual framework of the proposed reliability-based approach for life-cycle cost design of degrading concrete structures could be modified to accommodate various structural degradation condition. Here, it is modified to express the life cycle cost (LCC) based on the concept of SHMBM as follows[25].

$$LCC = C_I + \sum_{i=1}^{m} C_{MBM}{}^{i} + \sum_{j=1}^{n} C_{REP}{}^{j} + C_D \tag{2}$$

where $C_{MBM}{}^{i}$ is the monitoring based maintenance cost at i^{th} interval and $C_{REP}{}^{j}$ is the repair cost at j^{th} interval. Fig.4 shows that the healthy degree of an aging structure will reduce following a standard degradation curve. Therefore, monitoring based maintenance is necessary to extend its structural life. It is assumed that during a structural life cycle, there will be *m* intervals of monitoring and *n* intervals of repair of the infrastructure.

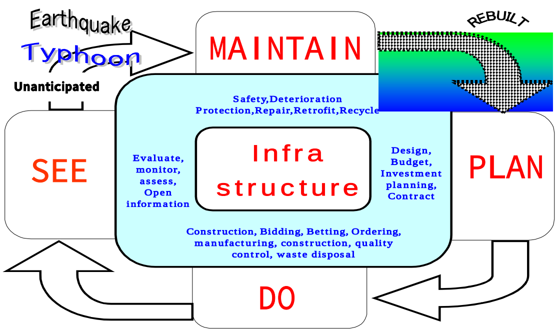

Fig.3. Management flow of SHMBM

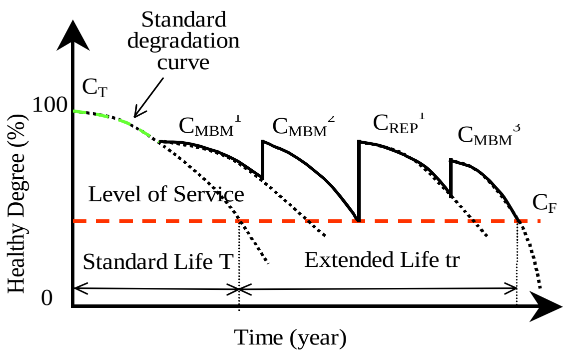

Fig.4. Schematic description of life cycle cost

2.2 The Effectiveness of SHMBM

The challenge in using the proposed approach is quantifying the uncertainties in the input variables. The rate of degradation, quality of inspection method, and cost of failure are often subjective and difficult to obtain, but their values have a great effect on the final result. With reliable input data, it offers the real potential for integrating economic and safety issues in structural design.

This approach serves as an initial base on which to develop improved life cycle cost design models. These models have to address additional issues such as serviceability limit states, use of spatially distributed random fields for describing the degradation process, use of Bayesian theory for estimating the probability of damage detection, use of improved time-variant bridge reliability models, reliability updating of target reliability level and development of user costs.

In our previous study on the monitoring of the corrosion expansion of reinforced concrete (RC) beam which was modeled as shown in Fig.5[26], by utilizing this approach to evaluate the economic and safety of an existing RC structure with a non uniform interval inspection strategy with the following assumptions:

(1) service life of the RC structure is 100 years;

(2) routine maintenance is scheduled once every two years;

(3) in the analyses, all inspection costs are converted to the initial cost of the structure, it is concluded that minimum LCC can be achieved in a certain quality of inspection technique.

The relationship of the expected inspection cost and LCC in various $\eta_{0.5}$ is shown in Fig.6. $\eta_{0.5}$ is the damage intensity at which the non-destructive evaluation (NDE) method has a 50% probability of detection.

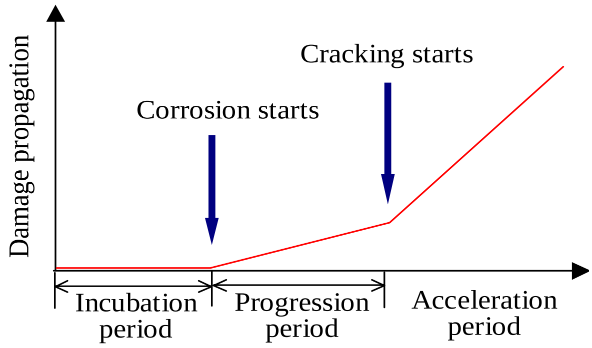

Fig.5. Reinforced concrete structural corrosion model

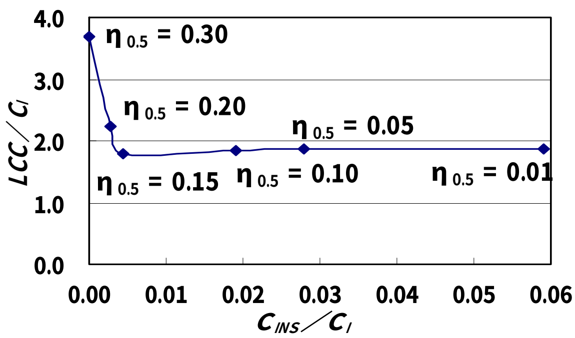

Fig.6. Optimization of life cycle cost

3. INTELIGGENT SENSORY TECHNOLOGY

3.1 General

Structures normally behave elastically which are designed to deform and reverse to their original configuration. When a structure is loaded beyond its normal limits, it behaves plastically and becomes permanently deformed and weakened. Often this damage is invisible, but as strains in the structure increase and the structure edges closer to structural failure. For instances, changes in girder strains, joint rotations and crack growth are indicators for evaluating structural integrity. By monitoring such changes closely, it is possible to provide quantitative clarity to assess structural health[19].

A real time monitoring system with a digital network to acquire, process, store and transmit the measured data is discussed. The proposed real time monitoring system provides valuable information for directing timely maintenance relief to those areas of the structure most in need of repair, so the following items can be achieved:

(1) Planned repair or replacement of the structure before catastrophic collapse;

(2) Improved allocation of scarce maintenance funding for the highest risk structure member;

(3) Determination of structural health after catastrophic events, such as, earthquake, typhoon, fire, explosions.

Here, developments of innovative high performance sensory technology and their capability as shown in Table 1 together with a real time monitoring system are provided and discussed.

Table 1 Sensory technology and their capability

No.	Sensory technology	Capability
1.	GPS-based MMS monitoring technology	Global deformation
2.	Peak memory sensory technology	Peak deformation
3.	Elasto-magnetic sensory technology	Actual stress
4.	Fiber Optic Sensory Technology	Displacement, temperature

3.2 GPS-based MMS monitoring technology

Global Positioning System (GPS) based Movement Measurement System (MMS) was developed by Geodev Earth Technology Switzerland. GPS based measurement has the advantages as weather independent, millimeters resolution, 3D displacement, long baselines, unnecessary of inter-visibility and "easy" to set up for outdoor applications. Specifically, the performance of this GPS based MMS monitoring technology can be concluded as follows:

1. Maximum baseline length (the distance between reference point and measurement station): 15 – 20 km;

2. Measurement frequency: maximum 2 measurements per hour;

3. Reliable measurement precision: 5 – 10mm.

The obtainable accuracy is dependent upon the satellite geometry, the number of satellites in operation, the atmospheric conditions and the number of measurement stations as shown in Fig.7. In order to monitor global structural movement of this structure, a GPS based MMS monitoring system is recommended[20]. Though the accuracy of this kind of measurement is in millimeters, the absolute coordinate can be grasped.

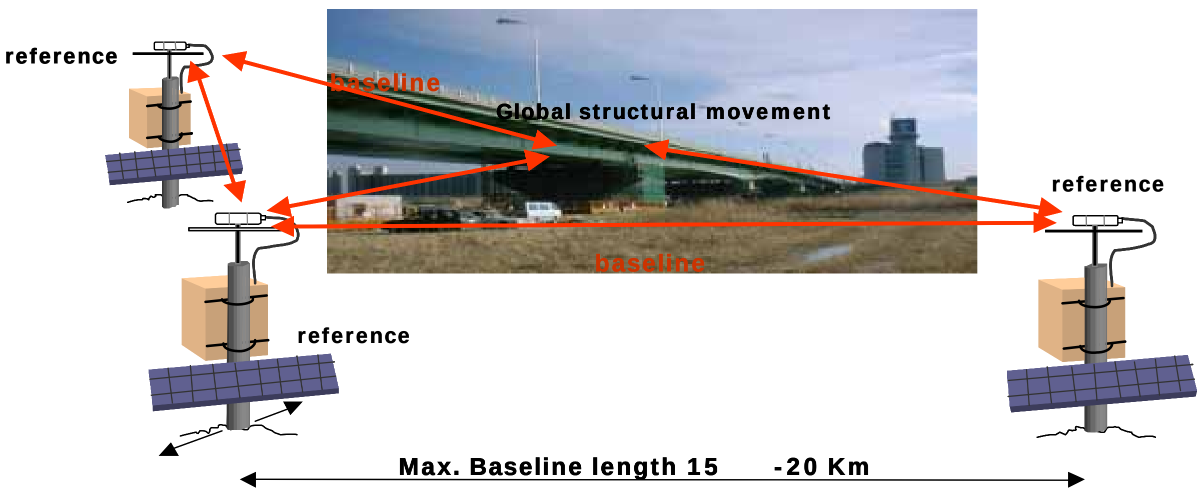

Fig.7. GPS-based MMS monitoring technology

3.3 Peak memory sensory technology

Peak Sensor with a digital data acquisition network has been developed[9]. As shown in Fig.8, the dual-output gauge measures peak compressive and tensile displacements with high precision and passively retains that value for later interrogation (Fig.9). Therefore, with one of these gauges, the structure after a critical event (such as earthquake or typhoon) can be interrogated, and the maximum distance of structure deformation during the event can be determined. These sensors require no electrical power except to read out the stored peak-displacement values[7]. Fig.10 shows the application of peak sensor on monitoring the peak displacement of bridge pedestal damper and Fig.11 shows the schematic description of PDMS (Peak Displacement Monitoring System).

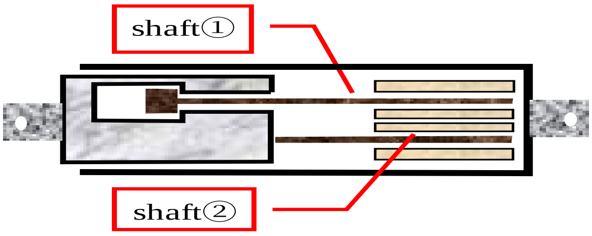

Fig.8. Schematic structure of peak sensor

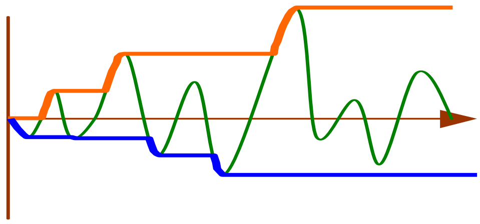

Fig.9. Peak values

Fig.10. Peak partial structural movement

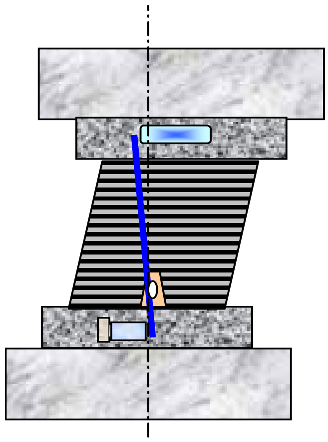

Fig.11. PDM system

3.4 Elasto-magnetic sensory technology

The elasto-magnetic (EM) sensory technology that can reliably monitor actual-stress in tendons and cables has been developed. This kind of sensor is a new approach to monitor ferromagnetic steel forces in concrete structures[9,26]. Based on the physical phenomenon that the permeability of ferromagnetic material is a function of magnetic history and applied fields, stress and temperature, permeability function is characterized at a technical saturation experimentally[12,17]. Besides fulfilling ‘$A_{to}E$’ characteristics, the sensor provides a theoretically unlimited service lifetime, can be applied to any structure built with circular steel reinforcements or cables and does not influence structural integrity in any way[12].

Pre-fabricated EM sensor takes the form of a hollow cylinder in the middle of which the measured element (wire, strand, cable, bar) passes through. It should be slipped onto the measured element beforehand, during the construction. Stress at each stage of loading condition can be monitored accurately[15]. This manufactured sensor consists of primary, secondary and compensating windings, mounted in a protective steel shield and sealed with an insulating material. EM sensor enables to measure the actual-stress in strands and cables protected by thin-wall steel tube or plastic tube without the need to remove them. This cylindrical EM sensor has no mechanical contact with the measured element so it will not be overloaded, it is resistant to water and mechanical injury, its characteristics does not change with time and its lifetime is closer to unlimited life time[22].

The EM sensory technology is a simple nondestructive evaluation technique (NDT) for monitoring stress in steel cables. The magnetization phenomenon is performed by two solenoids, i.e., a primary coil and a secondary coil as shown in Fig. 12, and Fig. 13 shows the bobbin as the axis of electric wires winding and the steel covers.

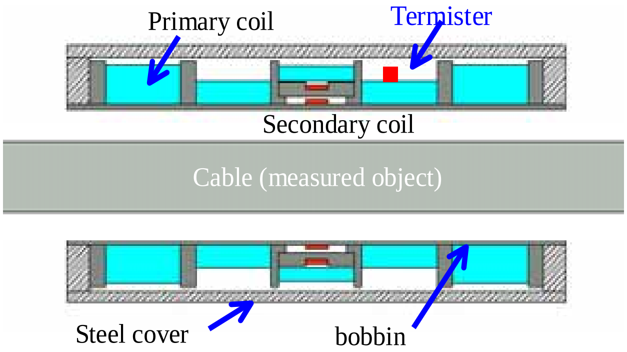

Fig. 12. EM sensor schematic structure


Fig. 13. Sensor bobbin and steel cover

3.5 Fiber optic sensory technology

In a general definition, fiber optic sensory system is defined as an optical data transmitting system which enables to measure material property quantities by a part or whole of an optic fiber and transmits those information by the same optic fiber. Furthermore, optic fiber sensory system enables to tackle material properties such as temperature, pressure, distortion, voltage change (electric current), magnetic field, velocity, vibration, displacement, gas pressure, moisture, salt concentration and radiation[13]. The advantages of fiber optic sensory system can be expressed as (i) remarkable dynamic range of measurement (from 1 micron to 10 percent strain); (ii) high resolution (about 1 micron for SOFO sensor); (iii) un-electric measurement system (thunder-proof and explosive-proof); (iv) high durability (suitable for SHMS purpose); (v) Enable to measure huge numbers of channel, simultaneously and in a long distance. There are numerous fiber optic sensory technologies available commercially[21]. Fig. 14 shows their schematic measured deformation for a concrete beam under flexural bending moment and Table 2 shows fiber optic sensor type classified by monitored length and possible number of sensors for one optic fiber.

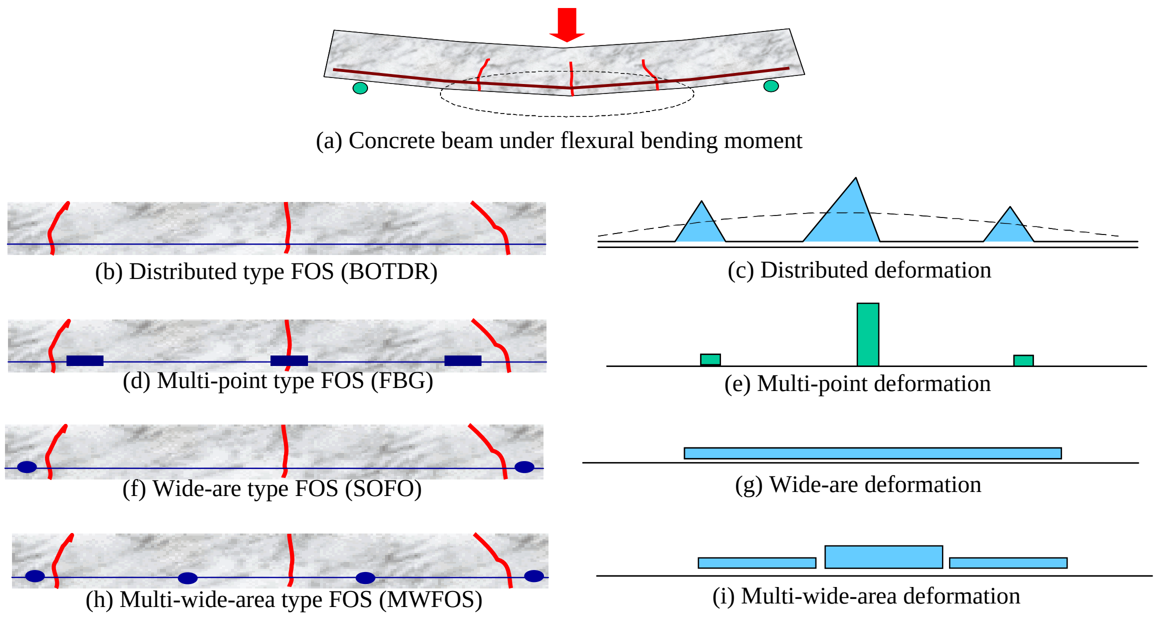

Fig.14. Measurement range classification of fiber optic sensory technology

Table 2. Type of Fiber optic sensor

No.	FOS Type	Nomenclature	Monitored length	Number of sensors
1.	Distributed type	BOTDR	Min 1m	20000 per 20km
2.	Multi-point type	FBG	1cm - 10km	12 sensors
3.	Wide-area type	SOFO	0.2m - 50m	1 sensor
4.	Multi-wide-area type	MWFOS	5cm – 30m	60 sensors

4. FIELD APPLICATION EXAMPLES

4.1 Peak displacement and peak stress monitoring

Bridge in Route 246 which is mainly configured by simply supported steel plate girder-bridge is located in a crowded traffic area in the center of Tokyo and servicing as a national traffic main route for over 37 years. One part of the route 246 bridges was pointed out to install some sensory technology which was integrated in a structural health monitoring system[7]. The 18 girders bridge has a length of 36m, width of 40m, and 8 traffic lines which is 4 traffic lines for each direction. Fig. 15 shows the overview of this bridge in route 246, Tokyo, Japan. In order to monitor the structural peak strain and/or peak displacement due to earthquake and heavy traffic impact loads, TRIP (Transformation Induced Plasticity) steel type sensors were installed in this site. The sensor whose function as peak strain sensor was installed in the middle of girder G5 as shown in Fig.16 and as peak displacement sensor was installed in the pedestal of the same girder.

Fig. 15. Bridge in route 246, Tokyo

Fig. 16. Peak strain data retriever

4.2 Actual stress monitoring on space structure

The Kumagaya Dome is a huge elliptical space structure with major axis length of 250m, minor axis length of 150m and height of 45m. The roof is supported by a dome structure with 1200 bracing cables in a 3D wire frame model as shown in Fig. 17.

Up to now, current strain gauge and/or torque method are commonly applied to control the displacement during construction stage. However, those measurement methods cannot provide structural de-formational information during service life of the structure. Therefore, EM sensory technology was introduced and installed in the middle as shown in Fig. 18 to monitor the actual stress of bracing cable. EM sensors were installed at half of the 1200 bracing cables to enable to monitor global structural movement of the space structure together with an actual-stress monitoring system as shown in Fig. 19. It can be considered as ‘a breakthrough in space structure construction method’ from short-term strain-monitored construction method to long-term actual-stress-monitored construction method.

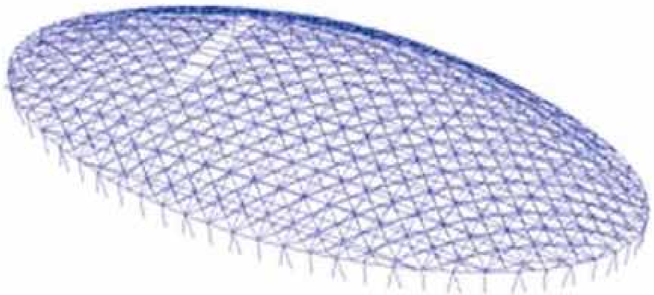

Fig. 17. 3-dimensional wire frame model of Kumagaya Dome

Fig. 18. EM sensor configuration

Besides actual stress controlling during 'jack-up and jack-down' construction stage as shown in Fig. 20, this monitoring system enables to figure-out any desired sectional stress distribution as shown in Fig. 21. For the sake of convenience in controlling the actual stress of each cable bracing, the monitoring system capability in expressing the history of wire stressing and summary of wire stresses were implemented as shown in Fig. 22. Stress sensor that can reliably monitor true-stress in tendons and cables has been developed. The elasto-magnetic sensor is a novel new approach to monitor cable forces in bridge cables and anchorages[13)]. Based on the fact that the permeability of ferromagnetic materials is a function of magnetic history and applied field (stress and temperature), permeability function is characterized at technical saturation experimentally. Besides fulfilling '$A_{to}E$' characteristics, the sensor boasts a theoretically unlimited service lifetime and can be applied to any structure built with circular steel reinforcements or cables and does not influence structural integrity in any way.

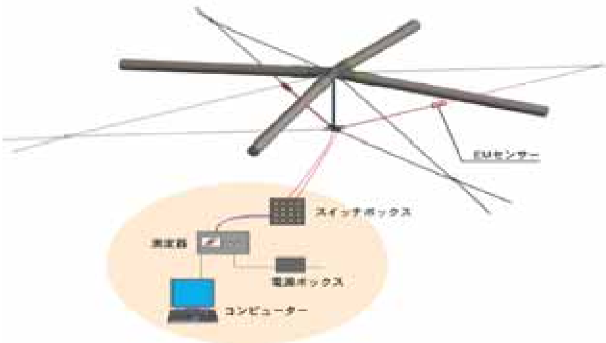

Fig. 19. Actual-stress monitoring system

Fig. 20. Dome Jack-up construction stage

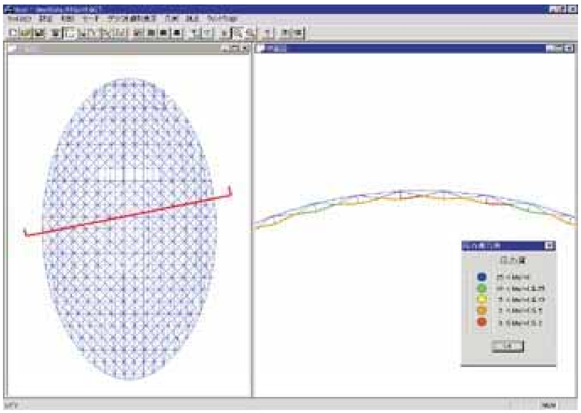

Fig.21. Sectional stress distribution

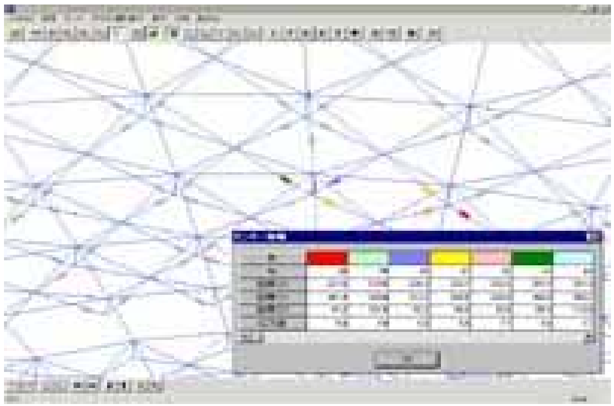

Fig. 22. History of wire stressing

4.3 SOFO sensors monitoring on existing tunnel deformational properties

SOFO is the French acronym of Surveillance d'Ouvrages par Fibres Optiques (or structural monitoring by optical fibers). The measurement setup is based on a double, all-fiber, Michelson interferometer in tandem configuration as shown in Fig. 23[2,3].

The SOFO sensor consists of pair of single-mode fibers installed in the monitored structure. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself, while the other, the reference fiber, is placed loose in a neighboring pipe[23]. All deformations of the structure will then result in a change of the length difference between these two fibers. Lengths of SOFO sensors are 500mm, 1000mm, 3000mm and 10,000mm in standard and up to 50,000mm with a special order. The main characteristics of the sensors and reading unit in an integrated system are listed in Table 3.

Table 3. The main characteristics of the SOFO integrated system.

Precision	Better than 0.2% of the measured deformation
Resolution	2 microns (independently from the gage length)
Dynamic range	1% in elongation and shortening (sensors)
(Maximum measurable deformation)	Up to 150mm in elongation and shortening (reading unit)
Stability	Drift not observed over six years
Measurement speed	Less 10 seconds for each sensor
Others	Rugged, portable and autonomous reading unit. Sensors can be embedded inside concrete for new structures (see Photo 1) and/or surface attached on existing structures (see Photo 2)

The management and the security of tunnels require periodical monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed and although they rarely affect the global structural security, they can lead to durability problems. Furthermore, an accurate knowledge of the behavior of a tunnel is becoming more important as new building techniques are introduced and the existing tunnels are required to remain in service beyond their theoretical service life. Monitoring, both during construction and in the long term, helps to increase the knowledge of the real behavior of the tunnel and in the planning of maintenance intervention[4,5].

The Shimakawahara Tunnel was constructed in 1970s for flowing wasted water as a part of sewerage network. The tunnel was made of concrete with height of 4,740mm, width of 4,200mm and length of about 5km as shown in Fig.24.

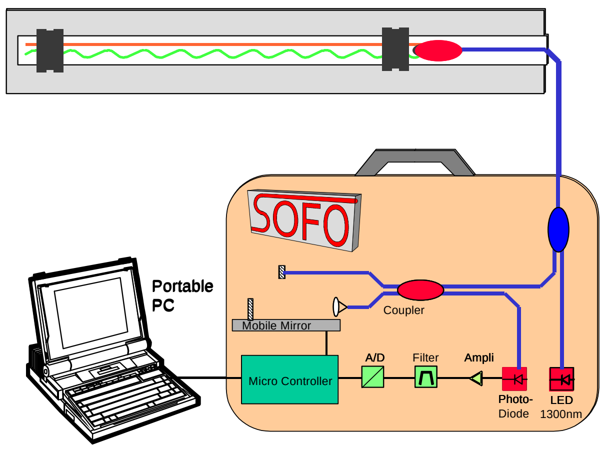

Fig. 23. SOFO monitoring system.

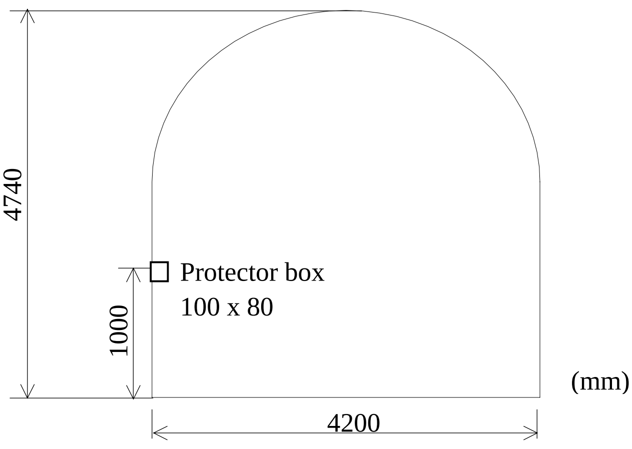

Fig.24. The cross-section of the Shimakawahara Tunnel.

Even a number of cracks have appeared spreadly and have been sealed with appropriate treatments, a reliable monitoring system in which enable to grasp the structural health behavior is expected. To maintain the serviceability of tunnel a monitoring is pro-posed by utilizing SOFO sensory technology. The aim of monitoring is to monitor the structural health degradation due to environmental evolution and mechanical evolution such as dynamical stress of streaming water. In order to monitor the global deteriorated structural deformational properties, 5 of 10m long-gage optical fibers were installed. The sensor configuration is shown in Fig.25 and the attachments are shown in Fig.26.

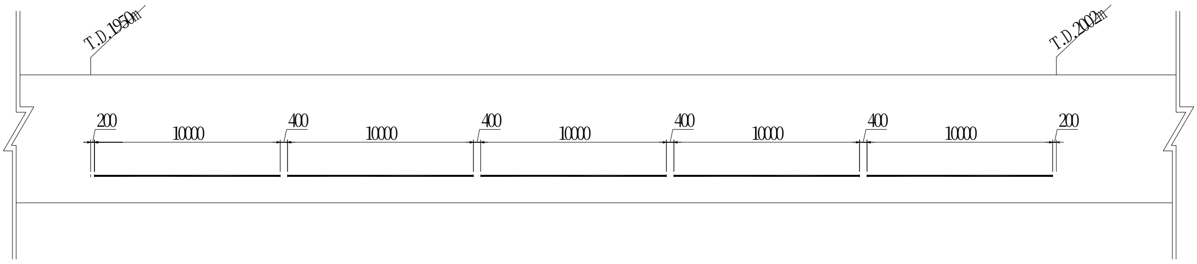

Fig.25. The sensor configuration (5 of 10m long-gage).

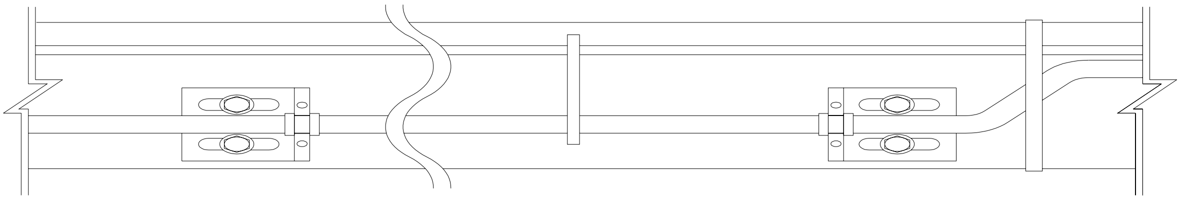

Fig.26. The sensor attachments.

Since the durability of the sensor will be affected by streaming water and attacks of garbage, the knight sensor, active and passive zones, was covered by protector box of 100mm x 80mm as shown in Fig.27. To avoid stream turbulence occurrence, the tip of the protector was manufactured as shown in Fig.28. The periodical monitoring was performed once a year.

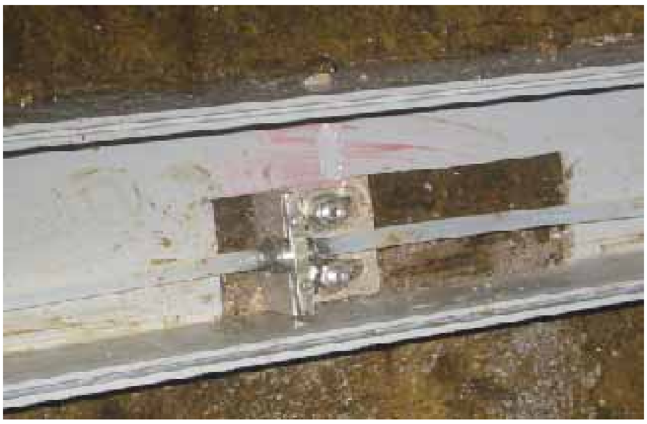

Fig. 27. Protector box

Fig. 28. The tip-end of the sensor protector

5. CONCLUDING REMARKS

As the concluding remarks it is summarized as:

1. Efficient monitoring technique and related effective technologies in the areas of structural health monitoring may improve lifecycle performance of infrastructures in which derive to a LCC reduction.

2. To improve sensory technology development, the following items should be taken into consideration, i.e., sensor material innovation, assembly technology, installation knowledge, data assessment knowledge, and 'how to provide SHMS in a reasonable PRICE'.

3. Structure Health Assessment technique development together with structure analyses in mechanical, chemical and environmental approaches are absolutely necessary to evaluate time-domain and/or spatial-domain structural anomalousness.

4. Some applications of structural health monitoring system are briefly reviewed The site-applicable real time monitoring system provides valuable information for directing timely maintenance relief to those areas of the structure most in need of repair, so the following items can be achieved:

    a) Planned repair or replacement of the structure before catastrophic collapse;

    b) Improved allocation of scarce maintenance funding for the highest risk structure member;

    c) Determination of structural health after catastrophic events, such as, earthquake and/or typhoon.

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