SUSTAINABILITY-BASED STRUCTURAL HEALTH MONITORING SYSTEM

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ABSTRACT

As the role to provide social lifeline, numerous of infrastructures have been constructing. Systematical maintenance management is needed to keep the sustainability of those infrastructures in a capable performance. The structural reality of existing structures is located in the field site, therefore how to retrieve field-monitored data is a challenge for field engineers. Structural Health Monitoring Based Maintenance (SHMBM) is a civil infrastructure maintenance philosophy based on input provided from field-monitored data. Structural health monitoring system (SHMS) consists of an array of sensors designed to provide the desired information required to make informed maintenance and repair decisions.

Human memory limitation, job position transformation, imperfection and inability to provide a reliable monitoring system can lead to overly optimistic reports on structural health. Therefore, the SHMS should be sustainable. In this paper, sustainability-based structural health monitoring system is discussed by reviewing the $A_{to}E$ characteristics of SHMS. Furthermore, new innovative sensory technologies are introduced to monitor global structural movement, partial structural movement and local structural deformational properties.

1. INTRODUCTION

Along the years of civilization, human beings have been creating innumerable infrastructure systems for residence, industrial, defense and other various purposes. These heritages have been accumulating as a huge inventory of structures now. Maintenance management of infrastructures has been one of the particular concerns of the engineering community and responsibility of the citizens to deliver these heritages in a feasible performance to the next generation. The main objectives of the maintenance management are to manage life cycle of structure in a most reasonable way to provide safety and healthy performance systematically, and to keep in a minimum level of lost due to hazards and other unanticipated loads.

Structural Health Monitoring Based Maintenance (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 can be assessed by performing continuous Structural Health Monitoring System (SHMS) on the structural deformational properties (Sumitro,et.al., 2001 and Sumitro, et.al., 2002). The essence of SHMS can be considered to involve measurement, inspection, and assessment of in-service structures on a continuous basis with minimum labor requirement. Sustainability based SHMS should fulfill $A_{to}E$ characteristics, i.e., Accuracy, Benefit, Compendiousness, Durability and Ease in operation. Generally, those characteristics are difficult to be compared quantitatively. Specifically, some qualitative-compared sensory technologies will be reviewed in this paper.

2. THE SCALE OF STRUCTURAL HEALTH MONITORING

For a monitoring system design engineer, the most essential points are reliability and sustainability of the SHMS in which reflected in accuracy of the applied sensory technology. The required accuracy depends on item and monitored object as shown in Table 1.

Table 1: The scale of monitored objects

Item	Monitored object	Required accuracy	Possible sensory technology
Global structural movement	Displacement	Teen-millimeters	MMS
Partial structural movement	Displacement	One-tenth millimeters	PDMD
Local structural deformational properties	Concrete strain	MPas	FOS
	Steel stress	MPas	EM sensor

Figure 1 gives an illustration on SHMS for continuous box-girder bridge. In order to monitor global structural movement of this structure, a GPS (Global Positioning System) based MMS (Movement Monitoring System) as shown in Figure 2 is recommended. Though the accuracy of this kind of measurement is in millimeters, the absolute coordinate can be grasped. Then, in case of monitoring partial structural movement such as bridge-pedestal-damper relative movement, PDMD (Peak Displacement Memory Device) as shown in Figure 3 is recommended. The accuracy of PDMD is range within one-tenth millimeters. Finally, in the purpose to monitor structural deformational properties, detailed monitoring systems which enable to provide precise field data is recommended such as high accuracy FOS (Fiber Optic Sensor) to monitor concrete strain (Inaudi,et.al., 1997) as shown in Figure 4 and EM (elasto-magnetic) sensor to monitor steel stress (Sumitro, 2001) as shown in Figure 5.

Figure 1: Continuous box-girder bridge as SHMS illustration example

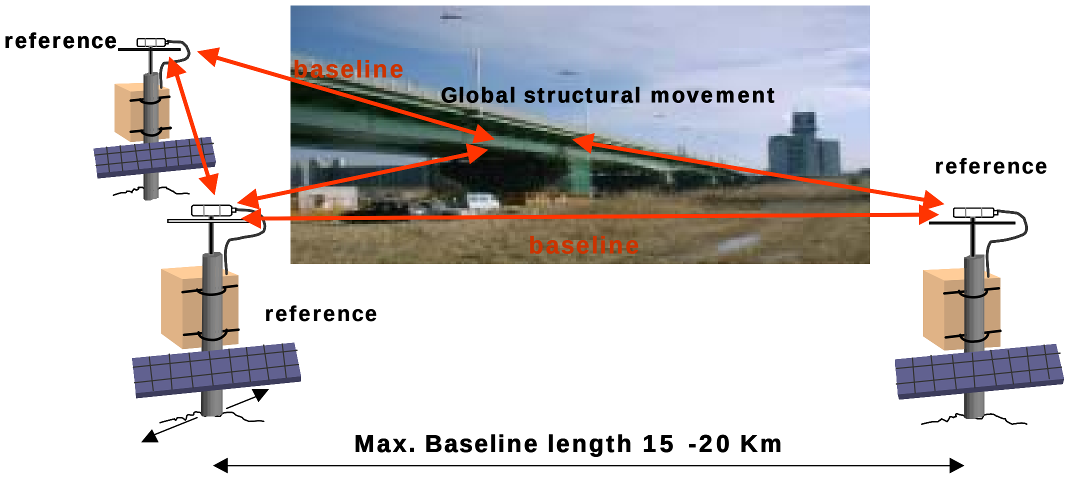


Figure 2: GPS – MMS to monitorr global structural movement

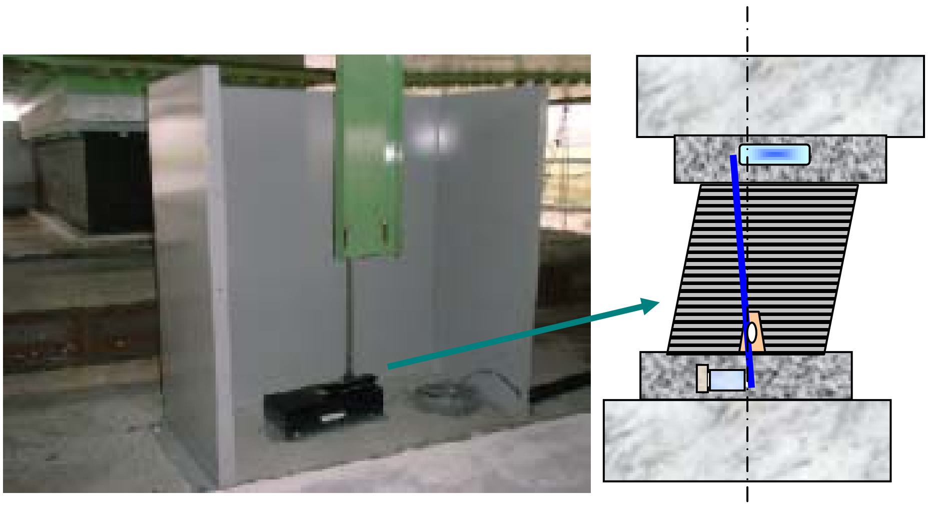


Figure 3: PDMD to monitor partial structural movement

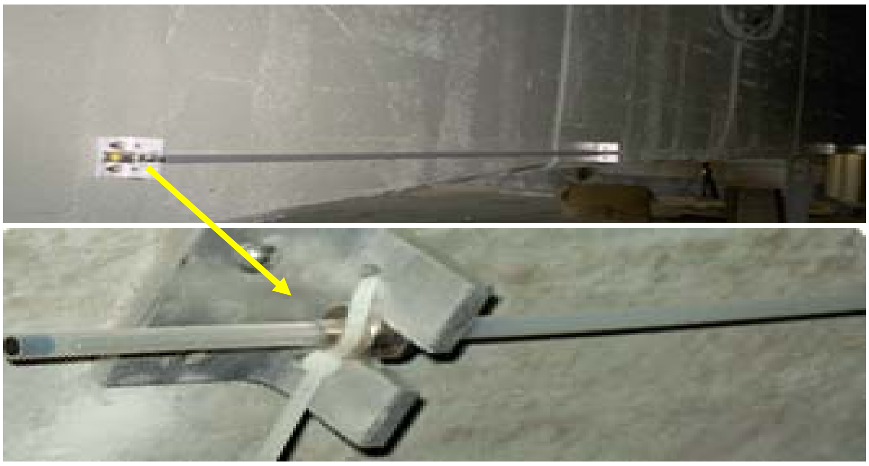


Figure 4: FOS to monitor structural deformational properties (strain)

Figure 5: EM sensor to monitor local actual-stress

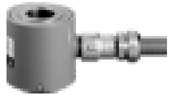
3. SUSTAINABILITY-BASED SHM CHARACTERISTICS

Sustainability based SHMS should fulfill $A_{to}E$ characteristics, i.e., Accuracy, Benefit, Compendiousness, Durability and Ease in operation. Some qualitative-compared sensory technologies are reviewed as follows.

3.1 Accuracy

Sensory technology should have a reliable accuracy. Commonly, the required accuracy in designing a suitable monitoring system depends on the monitored object. As an example of monitoring accuracy consideration, load cell (type: KCM-200KNA), stress meter (type: KSA-13A), strain gauge (type: FLA-3-1t-3LT), and EM sensor (type: EM d13) are compared as shown in Table 2. By the accuracy knowledge of possible sensory technology, a monitoring system designer can scope the desired monitored-data range.

Table 2: Monitoring accuracy (example)

Type of sensor		**Accuracy**
Load cell KCM-200KNA		Approx. 70kN $^{*)}$
Stress meter KSA-13A		Approx.0.1N/mm$^{2\ *)}$ D13mm(A=132): 13N
Strain gauge FLA-3-1t-3LT		Approx.1x10$^{-6\ *)}$
EM sensor EM d13		Approx. 1Mpa D13mm(A=132): 130N

Note : $^{*)}$ sensor resolution.

3.2 Benefit

In order to provide sufficient sensor density for a reliable monitoring system, commercial price of the sensory technology should be reasonable. As an example of monitoring beneficial consideration, load cell (type: KCM-200KNA), stress meter (type: KSA-13A), strain gauge (type: FLA-3-1t-3LT), and EM sensor (type: EM d13) are compared as shown in Table 3. In this example, the Monitoring cost was normalized into one piece of strain gauge commercial price in Japan. By the having sensor beneficial knowledge of possible sensory technology, a monitoring system designer can plan a economical SHMS.

Table 3: Monitoring cost estimation (comparison example)

Type of sensor	**Unit cost**	**Installation cost**	**Measurement cost**
Load cell  KCM-200KNA	234s $^{*)}$ T. cable s/m	174s (Direct cost)	80s (TDS-303: 165s/mt)
Stress meter  KSA-13A	74s T. cable s/m	246s (Direct cost)	80s (TDS-303: 165s/mt)
Strain gauge  FLA-3-1t-3LT	s/piece polish cost: 6s adhesive agent :7s	106s (Direct cost)	80s (TDS-303: 165s/mt)
EM sensor  EM d13	90s	-	80s (M. unit: 150s/mt)

Note : $^{*)}$ s = commercial price of one strain gauge

3.3 Compendiousness

For external attached sensor, compendiousness of sensor does not effect to local structural fracture. In case of sensor which is casted inside concrete, sensor should be simple and small enough. For instance, the newly developed cylindrical pulsed EM sensor has relatively small diameter compared to others previously magnetic based sensors. Outer diameter depends on the number of winding coils and they can be designed to be slender with longer in longitudinal direction. Therefore, it can be concluded that EM sensor enables to fulfill compendiousness characteristic.

3.4 Durability

As the example in consideration on the durability characteristic, reliability of the EM sensory system is discussed. EM sensor that can reliably monitor actual-stress in steel tendon and cables has been developed based on the fact that the permeability of ferromagnetic material is a function of magnetic history and applied field such as stress as shown in Figure 6 (Sumitro,et.al., 2002). The EM phenomenon 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 Figure 7. By examining the sensor schematic structure, the sensory durability depends on a few parts, i.e., copper wire, potting compound, steel cover and connecting cable.

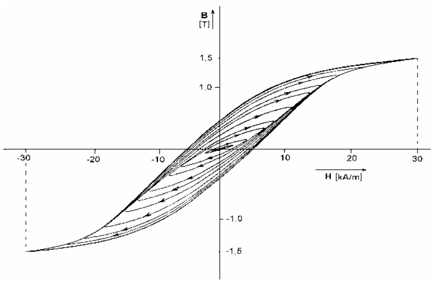


Figure 6: Magnetic hystereses

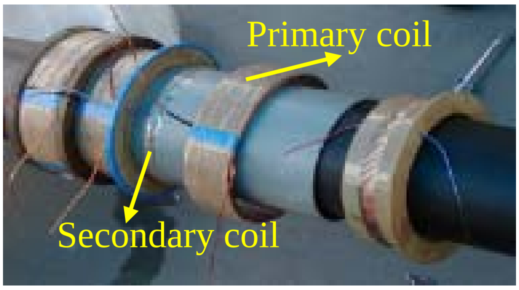


Figure 7: EM sensor schematic structure

The copper wire has very high durability, in case sheathed with special insulations it maybe sustain for hundreds of years. The copper wire is also protected by potting compound. The steel cover may be plated and protected against corrosion. In case of embedded in the concrete, the steel cover is off course protected against corrosion. The weakest point of the EM sensor is the connecting cable. The reliable cable for heavy-duty applications is expensive, but reliability is ever expensive. By investigating all the durability factors, in the industrial environment, the minimum lifetime of the EM sensor can be predicted to be 50 years. The measuring unit is not critical, because the measuring conditions are precisely defined and it is possible to replace the damaged measuring unit parts. Even after the long time operation, the current measuring unit can be replaced by a new type one. Off course after 50 years the computer era will be replaced by more advance version, the electronics parts, used in the measuring unit will be no more available but the physical principle will be the same and the measured steel cable will be also the same. The configuration of the windings and number of turns do not change with time.

As the example, EM sensors were installed at the strands 0.6 inch in the anchor for measuring the stress distribution between the single strands in the cable, integral sensors at the grouted cables and external tendons for measuring the total force, friction coefficients and long time stress loss at the Lafranconi bridge over the Danube river in Bratislava, constructed in period 1987-1990, and still reliably in service now (see Figure 8). It can be concluded that EM sensor is one of the most sustainable sensors. Comparing with the resistive strain gauges the EM sensor has infinite lifetime. The main advantage of the EM sensor is contact-less transfer of the stress from the measured cable to the sensor, and no glue as of resistive strain gauges, no mechanical contact as of vibrating wire gauges and annular dynamometers.

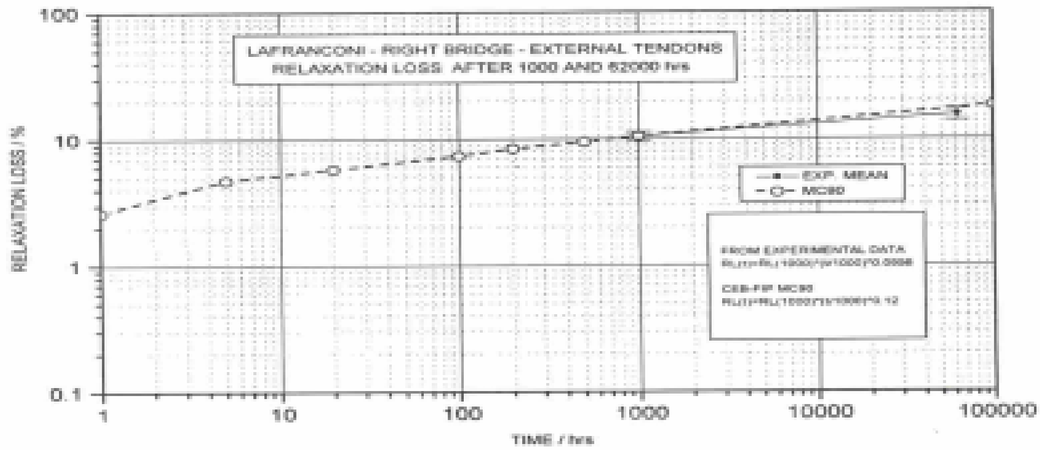
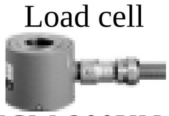


Figure 8: EM sensor application since 1987

Table 4: Ease in operation (comparison example)

Type of sensor	Installation ease
Load cell  KCM-200KNA	Though only enable to measure stress at end of tendon, expert knowledge is needed to avoid structurally error influence.
Stress meter  KSA-13A	Impossible to measure stress from the surface of sheath cover, and welding process is need to fix the position of sensor.
Strain gauge  FLA-3-1t-3LT	Surface polish and protection is necessary; For homogeneous result at least two gauges is needed to attach symmetrically in a steel bar; Stress is calculated based on empirical elastic modulus.
EM sensor  EM d13	Simply inserted to measure stress at arbitrary section; Possible to measure the mean stress from the surface of sheath cover (steel or plastic); Enable to measure the actual stress including dead load.

3.5 Ease

Sensory technology application procedure should be ease in operation, user-friendly, and time consumed for measurement should be close to real time measurement. Table 4 shows ease in operation by comparing load cell (type: KCM-200KNA), stress meter (type: KSA-13A), strain gauge (type: FLA-3-1t-3LT), and EM sensor (type: EM d13).

4. CONCLUDING REMARKS

The concluding remarks can be summarized as follows:

1. Systematic health assessment paradigm for investigation and documentation of as-constructed structures, local and/or global structural health condition are needed to preserve the huge inventory of infrastructures.
2. By observing numerous field measurement results, it is confirmed that EM sensor is a non-destructive, no-contact, easy to operate measurement system to measure actual stress of steel wires, bars and cables. Over 17 years experience confirms that EM sensory technology is reliable, accurate and generally applicable to many structural monitoring situations, even when other methods are inapplicable.
3. 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’.

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