CORROSION MONITORING BY UTILIZING EM TECHNOLOGY

Paul Sumitro
Smart Structures, USA

Andrej Jarosevic
Comenius University, Slovakia

Noriyuki Miyamoto
Keisoku Research Consultant Co., Japan

Stress of steel reinforcement for reinforced concrete member, strands for prestressing concrete and cables for suspension bridges are the most important parameters for assessing the health of existing bridge structures with cables. Elasto-magnetic (EM) sensors have been used extensively in measuring actual stresses of strands and cables of many types of constructions such as ground anchors, cable-stayed bridge cables, pre-stressed concrete tendons, spatial dome bracings and steel of reinforced concrete members. Through successfully credentials that have been conducted in the field, it is confirmed that EM technology is a viable method for long term cable monitoring. EM sensor enables to monitor stresses for external tendons on existing PC bridges, steel cables of existing cable-stayed bridges, and suspension bridges. EM sensor consists of copper wire windings for primary and secondary coils encapsulated in a protective steel cover and sealed with an insulating material. EM sensors enable to monitor the stresses on strands and cables protected by thin-wall steel or plastic sheathing without altering its original state. In a cable which is sustained under the constant force, by moving EM sensor along the cable, an abrupt change of magnetic permeability indicates either corrosion, breakage of strand, or boundary condition change. Corrosion sensitivity is about 1% of area loss.

Keywords: Bridge, steel cables, corrosion monitoring, EM sensor, Maintenance, Long-term Bridge Performance

Corresponding author's email: paul@smart-structures.com

CORROSION MONITORING BY UTILIZING EM TECHNOLOGY

Paul Sumitro[1], Noriyuki Miyamoto[2], and Andrej Jarosevic[3]

[1] Smart Structures LLC, Illinois, USA
[2] Keisoku Research Consultant Co, Tokyo, Japan
[3] Comenius University, Bratislava, Slovak

ABSTRACT: Stress of steel reinforcement for reinforced concrete member, strands for pre-stressing concrete and cables for suspension bridges are the most important parameters for assessing the health of existing bridge structures with cables. Elasto-magnetic (EM) sensors have been used extensively in measuring actual stresses of strands and cables of many types of constructions such as ground anchors, cable-stayed bridge cables, pre-stressed concrete tendons, spatial dome bracings and steel of reinforced concrete members. Through successfully credentials that have been conducted in the field, it is confirmed that EM technology is a viable method for long term cable monitoring. EM sensor enables to monitor stresses for external tendons on existing PC bridges, steel cables of existing cable-stayed bridges, and suspension bridges. EM sensor consists of copper wire windings for primary and secondary coils encapsulated in a protective steel cover and sealed with an insulating material. EM sensors enable to monitor the stresses on strands and cables protected by thin-wall steel or plastic sheathing without altering its original state. In a cable which is sustained under the constant force, by moving EM sensor along the cable, an abrupt change of magnetic permeability indicates either corrosion, breakage of strand, or boundary condition change. Corrosion sensitivity is about 1% of area loss.

Keywords: Bridge, steel cables, corrosion monitoring, EM sensor, Maintenance, Long-term Bridge Performance

1 INTRODUCTION

Structure Health Monitoring System development, such as, evaluation of the field condition of existing structures and to monitor the important engineering properties of new structures, can be considered as the first step in resolving of the above problem [Sumitro et al. (2001)]. New innovative evaluation methods need to be devised to assess the deterioration of infrastructures such as steel tendons, cables in cable stayed bridge and strands embedded in pre- or post-tensioned concrete beams [Kurokawa et al. (2002)]

However, no accurate and simple method is available for directly measuring the stresses and corrosion in steel cable in cable-stayed bridges and suspension bridges

[Sumitro et al. (2002)]. Stress monitoring is important especially to grasp cable stress due to excessive wind or traffic loading, to gage the redistribution forces present after seismic events, and to detect corrosion via loss of cross section of steel. These cables are often very large, containing several hundred small wires. The cables are sheathed in a plastic protective cover filled with cement grout, and the wires may be coated with lubricating compounds. For these reasons, conventional methods such as strain gages that have been used for much smaller pre-stressing cables are impossible to use in cable stays. Vibration frequency measured at the middle region of a cable is often used to determine the tension force. The uncertainties of the values of parameters such as mass, length, and cross section area can introduce a significant error to the actual force. Moreover, the stress near the anchor point is of real concern.

The Elasto-Magnetic technology is an innovative approach to monitor cable forces in pre-stressed structures and bridge cables [Jarosevic et al., (1996), Chandoga et al., (1997)]. This technology overcomes the above mentioned disadvantages related to vibrating frequency or strain gauge methods while still inhabiting the advantages of normal NDT methods [Sumitro et al., (2002)]. The Elasto-Magnetic Phenomenon is a simple nondestructive evaluation technique to monitor stress and corrosion in steel cables [Sumitro et al., (2003)].

2 THE BACKGROUND OF EM TECHNOLOGY

2.1 Elasto-magnetic characterization

The magnetic properties of ferromagnetic materials can be described by the magnetic domain theory. This theory postulates that material is made up of local regions called ferromagnetic domains, each magnetized to saturation but aligned according to the state of local magnetization. Adjacent domains are separated by a highly localized magnetic transition region called the domain wall. Even in the demagnetized state, all domains are still magnetized to saturation, but the orientation of the individual domain magnetization vector is random, which results in a net magnetization of zero for a specimen. The application of a magnetic field or a mechanical stress can change the configuration of the domains, principally by wall movement.

Ferromagnetic material with cross-section A_s is subjected to an external magnetic field with strength $H(t)$ by passing it through a sensor coil with N turns and area A_t. According to Faraday's law, voltage induced in the coil is given by time change of the total magnetic flux flowing through the coil,

$$V_{ind}(t) = -\frac{\partial \Theta(t)}{\partial t} = -\left[nA_s \frac{\partial B(t)}{\partial t} + n(A_t - A_s)\mu_0 \frac{\partial H(t)}{\partial t} \right] \quad (1)$$

Assuming a homogeneous magnetic field, the relative permeability of the measured material can be expressed as

$$\mu_r = 1 + \frac{A_t}{A_s}\left(\frac{V_{out}}{V_0} - 1 \right) \quad (2)$$

where V_{out} is the output voltage with the measured material and V_o is the output voltage without the ferromagnetic material. The corrosion of a cable results in decreasing of the

cross-sectional area of the steel material adopted, therefore, EM method can be applied to monitor the corrosion progression to assure long-term bridge performance.

2.2 Smart EM sensors

2.2.1 Pre-fabricated sensor

Pre-fabricated EM sensor takes the form of a hollow cylinder through which the steel element (wire, strand, cable, bar) passes through (see Figure 1). It should be slipped onto the steel element beforehand, during the construction. This manufactured sensor consists of primary, secondary and compensating windings, mounted in a protective steel shield and sealed with an insulating material. 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 estimated life is more than 50 years [Sumitro et al.(2007, 2009)]. These EM sensors also enable the stress measurement in strands and cables protected by thin-wall steel tube or plastic tube, without the need to remove them.

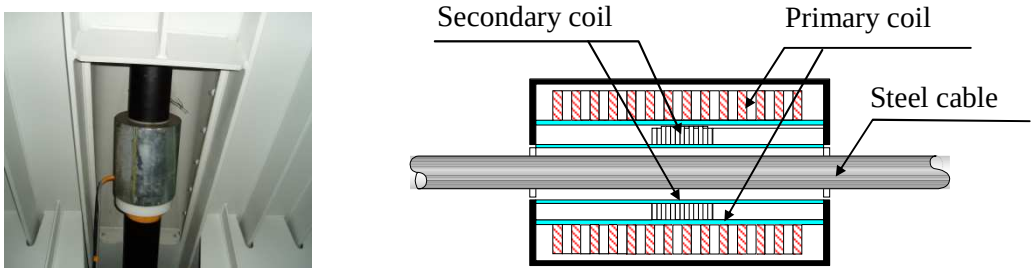


Figure 1. Pre-fabricated EM sensor for new construction bridge.

2.2.2 Site-fabricated sensor

This type of EM sensor enables f orce measurement in external tendons in outer cable PC bridge, steel cables in cable stayed bridge and suspension bridge, without the necessity to install the sensor during the construction period (see Figure 2). The accuracy of the measurement is lower due to some uncertainties during the field winding process. This EM sensor can also measure the real stress of cable even in the cases where zero stress state of the measured element is unknown.

Figure 2. Site-fabricated sensor for existing bridges.

3 ACCURACY AND RELIABILITY

Steel cable which consists of 13 strands d15.5mm with total cross sectional area 1839.5mm^2, was placed inside the EM sensor. One wire d5.5mm with cross sectional area 23.75mm^2 with air gap (wire was cut in the middle and a piece of plastics with length 5, 10, and 15 mm was inserted) was moved along the cable. Figure 3 shows the output voltage from the EM measuring unit.

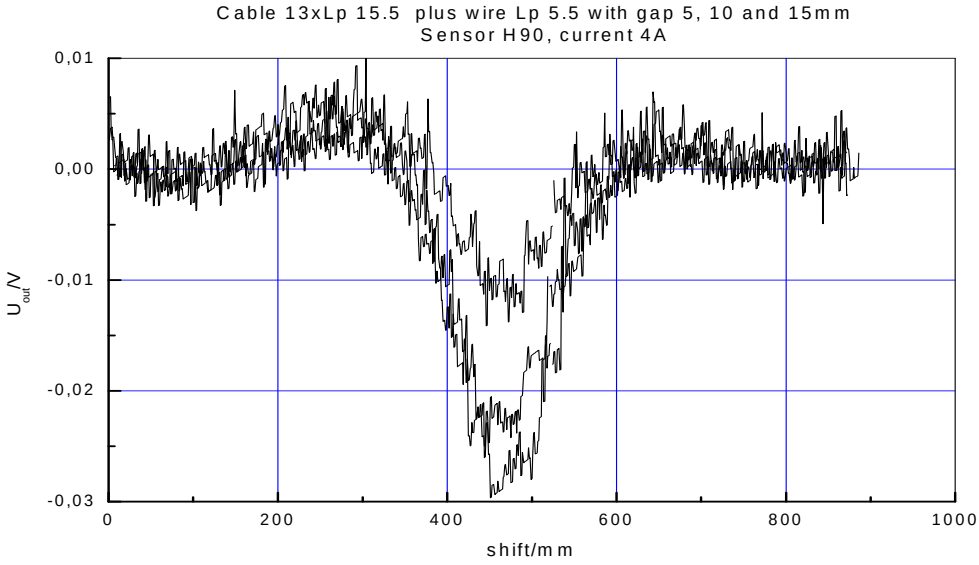


Figure 3. Monitored defeated area.

As shown in the verification test result that this EM technology is possible to detect inside-cable defect about 1% of the total cross-sectional area. Although the main goal of this experiment was to investigate the possibility of broken wires detection, by considering the result of this test, it is confirmed that EM technology is the only-one non-destructive method that can monitor corroded area quantitatively.

4 CORROSION MONITORING OF SUSPENDED CABLE

Two EM sensors were installed at cable No.5 and cable No.8, respectively (see Figure 4). Sensor configuration is shown Figure 5. Sensors were fabricated for existing cables of a mock-up test at Carleton Laboratory, Columbia University. Sensor at inclined cable No.8 was fabricated on 17 January 2008 and sensor at straight cable No.5 was fabricated on 13 March 2008. A cable pulling test was performed to verity its reliability. As shown in Figure 6, comparing with pressure gages installed at the cable-ends, accuracy of better than 5% was confirmed. Figure 7 shows the changes of force in cable No.5 affected by pulling of neighborhood cables.

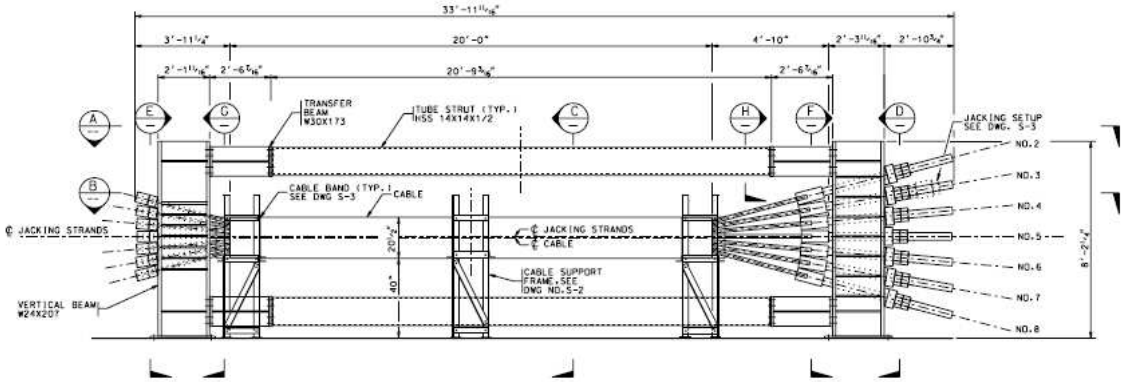


Figure 4. Test Setup

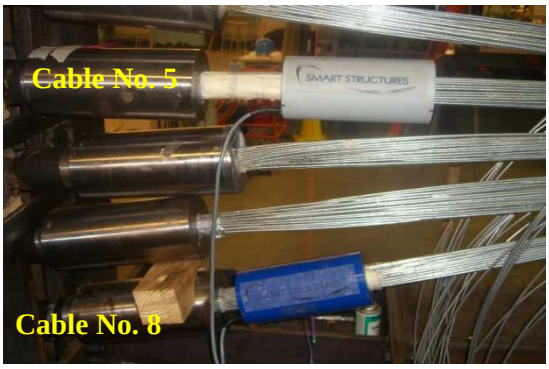


Figure 5. Sensor configuration

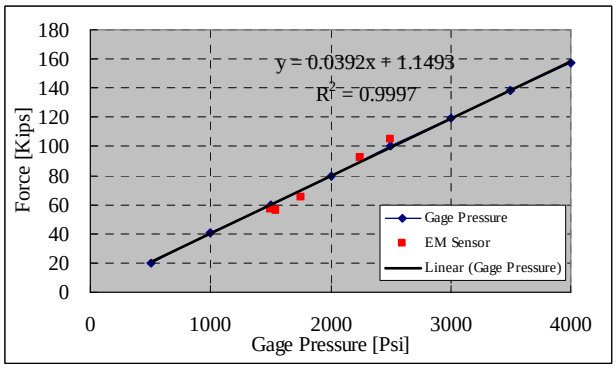


Figure 6. Test result

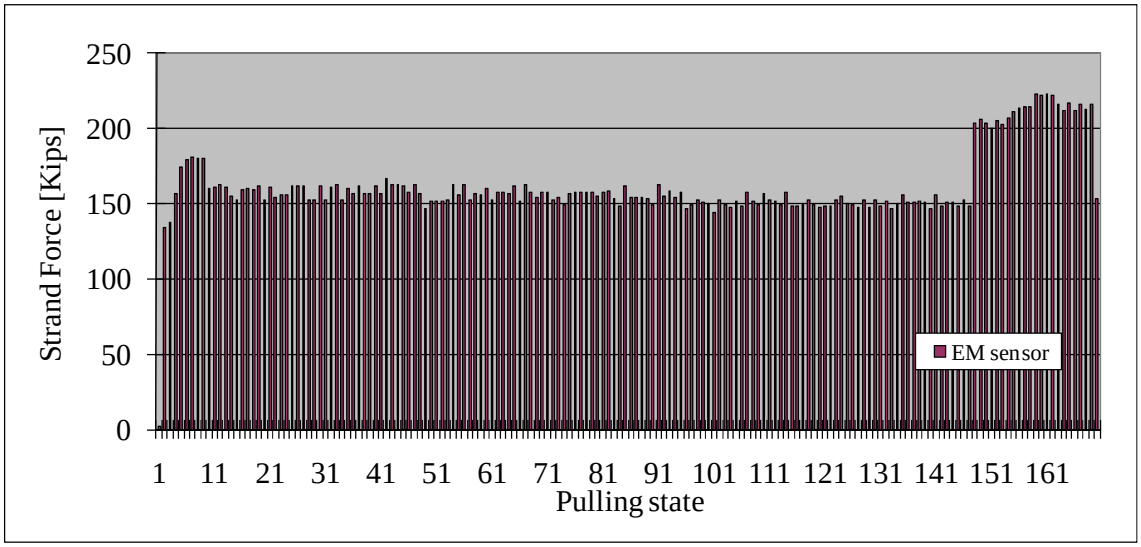


Figure 7. Cable No. 5 stress change

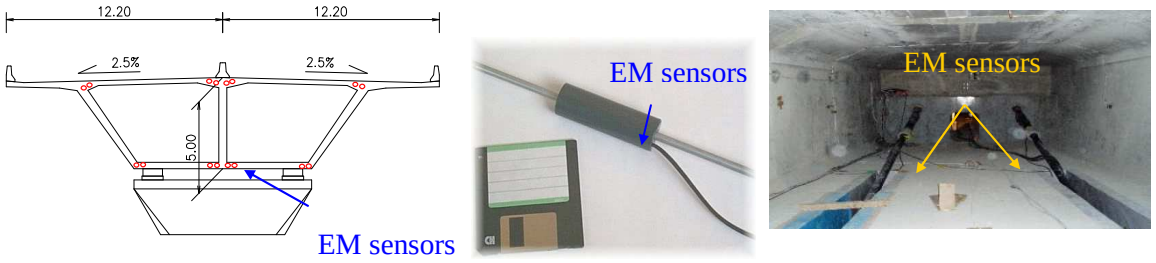
5 BRIGE APPLICATIONS

EM sensors have been applied at numerous numbers of bridges in the world. Especially when the other technology cannot be employed such as long-term stress monitoring for steel cables constructed bridges.

5.1 Pre-stressed concrete bridge

Installing EM sensor for a pre-stressed concrete bridge at construction stage, enables to monitor tendon stresses not only during stresses changes during construction, but also along service life of the bridge. Typically EM sensors (4x2x2) are proposed to install at each span as shown in Figure 8(a). In addition, small EM sensors with 5mm steel bars are recommended to install adjacent to pre-stressed tendons to monitor actual concrete compressive stresses due to pre-stress losses as shown in Figure 8(b).

In case of repair or retrofit for existing pre-stressed concrete bridges, EM sensors are the most effective technology to monitor actual stress of tendon for its entire history. Application on KRW bridges in Western Japan is one of the examples on the long-term monitoring of the structural performance after retrofitting (see Figure 8(c)).



(a) PC section (b) EM bar sensor (c) Retrofitted box girder PC bridge

Figure 8. Pre-stressed Concrete Bridge

5.2 Cable-stayed bridge and suspension bridge

In long span bridges, such as, cable stayed bridges and suspension bridges, the main purpose of EM sensory application is to control the quality during bridge construction, to compare the actual parameters of anchorages with the estimated ones, and to monitor long-term structural parameter changes due to aging deterioration, natural hazards and others un-anticipated factors.

Ashidagawa Bridge is a cable-stayed bridge located at Fukuyama City, Hiroshima prefecture Japan (see Figure 9(a)). Six EM sensors were installed in 3 different diameters (135mm, 155mm, and 165mm) of the total 18 cables. To keep original architectural view, the sensor was moved down in side the bridge chamber under the bridge deck (see inset). Four EM sensors were installed in stayed cables at TYS Bridge (Figure 9(b)) and eight EM sensors were applied to monitor the actual stress of vibration stabilizer cables in KSD Bridge as shown in Figure 9(c).

(a) Asidagawa bridge (b) TYS Bridge (c) Cable in KSD Bridge

Figure 9. EM sensor application in long span bridges

6 CONCLUDING REMARKS

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 and corrosion of steel wires, bars and cables. Therefore, this measurement technology is suitable for developing a health monitoring system for any cable constructed bridges such as pre-stressed concrete (PC) bridges, cable-stayed bridges and suspension bridges.

Since this direct stress sensor can be applied at existing cables, the actual stresses of existing cables can be monitored by this technology. Furthermore EM sensor can be utilized also for corrosion monitoring. By observing numerous field measurements and 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. The over longtime experience confirms that the EM sensory technology is reliable, accurate and generally applicable to many structural monitoring situations when other methods are inapplicable. Therefore, EM measurement technology is apparently suitable for the use in a long-term health monitoring system for measuring actual stress of steel cable that has been used for major long-span bridges in the world.

7 ACKNOWLEDGMENT

The authors would like to thank Eugene Mindlin Structural Deterioration Laboratory, Department of Civil Engineering & Engineering Mechanics, Columbia University and all other parties involved in the Corrosion Monitoring System Joint Research for their collaboration and support during Corrosion Monitoring Joint Research.

8 REFERENCES

Chandoga, M., Halvonik, J., Jarosevic, A. & Begg D. W. 1997. Relationship between design, modeling and in-situ measurement of pre-tensioned bridge beams, *Proceedings of the International Conference "Computational Methods and Experimental Measurements"*, Rhodes, Greece, 21-23 May, 1997.

Chen, Z., Wang, M.L., Okamoto, T., and Sumitro, S. : A new magnetoelastic stress/corrosion sensor for cables in cable-stayed bridges using measurement of anhysteretic curve, 2nd Workshop on ATUEDM, Kyoto, July 11-13, 2000

Jarosevic, A., Fabo, P., Chandoga, M., and Begg, D.W. : Elastomagnetic method of force measurement in prestressing steel, *Inzinierske stavby*, Bratislava, Slovakia, Vol. 7, pp.262-267, 1996

Jarosevic, A., Fabo, P., Chandoga, M., Begg, D.W. & Heinecke, O. 1996. The elastomagnetic method of force measurement in prestressing steel, Structural Assessment – The role of large and full scale testing, Joint Institution of Structural Engineers/ City University International Seminar, London, UK, 1-3 July 1996, 64.1-64.8

Kurokawa, S., Sumitro, S., Wang, M.L. & Shimano, K. 2002. Verification Test of EM Sensor Application on PC Tendon Actual-stress Monitoring, J. of Applied Mechanics, Vol.1, August, 2002

Sumitro, S, Okamoto, T., Matsui, Y. and Fujii, K. : Long span bridge health monitoring system in Japan, *Proc. SPIE 8th Annual International Symposium on Smart Structures and Material, Health Monitoring and Management of Civil Infrastructure Systems*, Newport Beach CA, Vol. 4337-67, pp.517-524, 2001

Sumitro, S. 2001. True-stress measurement of PC steels by EM sensor, Special edition on Advance Technology, J. of Prestressed Concrete Japan (JPCEA), Vol.43, No.6, Nov, 2001, pp.99-103 (in Japanese)

Sumitro, S, Tominaga, M, & Kato, Y. 2002. Monitoring Based Maintenance for Long Span Bridges, First International Conference on Bridge Maintenance, Safety and Management, IABMAS 2002, Barcelona 14-17 July, 2002.

Sumitro, S, Jarosevic, A, & Wang, M.L. 2002. Elasto-Magnetic Sensor Utilization on Steel Cable Stress Measurement, The First fib Congress, Concrete Structures in the 21th Century, Osaka, 13-19 October 2002, Session 15, pp.79-86.

Sumitro, S., Hida, K., & Le Diouron, T. 2003. Structural health monitoring paradigm for concrete structures, 28th Conference on Our World in Concrete & Structures, Singapore, 28-29 August 2003.

Sumitro, S., Hoashi, H., Okamoto, T. and Wang, M.L.: Removable Actual-Stress Sensor, Proc. Of the Third International Conference on Structural Health Monitoring of Intelligent Infrastructures, SHMII-3, Vancouver, British Columbia, Canada, November 14-16, 2007

Sumitro. S., Hiroshi, M., Itoh, Y. and Okamoto, T.: Line Sensor Scanner for Structural Health Monitoring, Proc. Of the 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure, SHMII-4, Zurich, Switzerland, July 22-24, 2009