ELASTO-MAGNETIC SENSOR UTILIZATION ON STEEL CABLE STRESS MEASUREMENT

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1 INTRODUCTION

Maintenance of the huge stock of infrastructures is one of the major concerns in the developed countries in this century. 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 [1]. 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.

However, no accurate and simple method is available for directly measuring the stresses in steel cable in cable-stayed bridges and suspension bridges [2]. The measurement of the stresses is important for monitoring excessive wind or traffic loading to gage the redistribution forces present after seismic events, and for detecting corrosion via loss of cross section of steel. These cables are often very large, containing several hundred wires of 7mm diameter. 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, invasive methods such as strain gages that have been used for much smaller pre-stressing cables are impossible to use with 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 a novel new approach to monitor cable forces in pre-stressed structures and bridge cables [3,4]. This technology overcomes the above mentioned disadvantages related to vibrating frequency or strain gauge methods while still inhabiting the advantages of normal NDT methods [5]. The Elasto-Magnetic Phenomenon is a simple nondestructive evaluation technique for monitoring stress in steel cables [6]. An experiment to verify the utilization of Elasto-Magnetic phenomenon on stress monitoring of steel cables was constructed. The magnetization phenomenon is performed by two solenoids, i.e., a primary coil and a secondary coil. Basic material parameters such as magnetic permeability, intensity of magnetization and temperature were obtained from calibration tests on 7mm wire. Then, these basic material parameters were used to measure the real stress in a 37x7mm diameter cable.

Comparison of measurement results with load cells yielded satisfactory agreements and thus it can be stated that utilization of Elasto-Magnetic Phenomenon is suitable for structural health monitoring.

2 THEORETICAL BACKGROUND

2.1 Characteristics of elasto-magnetism

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.
Depending on the material, magnetic properties are altered with the application of stress, the extent of the change being a function of the material itself. An explanation of this phenomenon can be described in terms of the internal potential energy of the magnetic domains as:

\[
E_\sigma = \frac{3}{2} \lambda_s \sigma \sin^2 \theta
\]  

where \( E_\sigma \) is the magnetic strain energy, \( \lambda_s \) is the bulk magneto-restriction strain that is induced when an un-magnetized material is magnetized to saturation magnetization, \( \sigma \) is the applied stress and \( \theta \) is the angle between the direction of the applied stress and the magnetization vector. From Eq.1 it can be seen that in order to minimize the magnetic strain energy, the magnetization vector needs to rotate when a uni-axial stress is applied, making magnetization in certain directions easier or more difficult. Therefore, by properly developing the relationship between magnetization and stress it is possible to measure the stress level in ferromagnetic materials.

The magnetization of a material is typically described by the relationship between the magnetic field strength, \( H \) (Amp-turns/m), and the flux density, \( B \) (Webers/m\(^2\)), and for any material can be expressed by the general constitutive equation

\[
HB = \rho \rho \mu
\]  

where, \( \mu \) is the magnetic permeability tensor[10]. However if the material is macroscopically homogeneous and isotropic, the relationship can be reduced to its scalar form and \( \mu \) is a scalar. Fig.1 shows a typical magnetization curve for a ferromagnetic material. It is evident that the permeability is not constant, but is dependent on the field strength. It should be noted that \( \mu \) is not the slope of the magnetization curve, but simply represents the ratio \( B/H \). One of the easiest ways to magnetize a material and study its magnetic characteristics is through the principle of magnetic induction and two solenoids, a primary coil and a secondary coil, with the material whose magnetic characteristics are to be investigated as the core. If a DC current is applied across the primary coil it produces a magnetic field \( (H) \) and the magnetic flux density \( (B) \) within the specimen. Amplitude permeability is defined as the ratio \( B/H \), and incremental permeability defined as the ratio \( \Delta B/\Delta H \) [7]. In both the cases, permeability depends also on “working point” at which it is measured.

![Fig.1 Typical B-H curve for a ferromagnetic material](attachment:Fig1.png)
2.2 Measurement method

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,

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

(3)

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

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

(4)

where $V_{out}$ is the output voltage of the measured material and $V_o$ is the output voltage without the ferromagnetic material [8].

2.3 Elasto-magnetic (EM) sensors

2.3.1 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 Fig.2). 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. 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.

![Fig.2 Schematic description of EM sensor structure](image)

2.3.2 Site fabricated sensor

This type of EM sensor enables force 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 Fig.3). The accuracy of the measurement is lower due to some uncertainties during the field winding process. Furthermore, this EM sensor also enables to measure the real stress of cable even in the cases where zero stress state of the measured element is unknown.

![Fig.3 Wound in-situ sensor](image)
3 STRESS ESTIMATION, ACCURACY AND RELIABILITY

3.1 Stress estimation
Both the amplitude and the incremental permeability are stress and temperature dependent, therefore, they can be used for stress estimation. Previously, during the long-time measurements the temperature error caused by sensor heating was significant, but now, this drawback has been eliminated by a recently developed pulse method of measuring the incremental permeability. The incremental permeability is measured during the duration of short and high current pulse so that the average energy dissipation is very small and no heating of sensor occurs [9]. Fig. 4 shows typical dependence of incremental permeability on the stress and temperature for the 7mm wire.

### Fig. 4 Incremental permeability Vs stress and temperature

![Graph of Incremental permeability Vs stress and temperature](image_url)

3.2 Accuracy and reliability
Uncertainty of the measurement by elasto-magnetic method is influenced by: (i) changes in the measuring system parameters with temperature and time; (ii) change in measured element temperature; and (iii) scattering of elasto-magnetic characteristics of the measured element and their change with time.

Before every measurement, the change of the measured parameters is excluded by auto-calibration (built-in the measuring unit). The temperature effect may be excluded mathematically, using the known temperature dependence of elasto-magnetic characteristics and the measured element temperature that is analyzed in a calibration state. The scattering of elasto-magnetic characteristics is obviated by sensor calibration with a sample of the real element used [10]. Changes of elasto-magnetic characteristics with time were observed by laboratory test and it is confirmed that long-time stability of the elasto-magnetic characteristics is high with 1% accuracy. The EM sensor characteristics (geometry of windings) are stable with time and expected life of the sensor is more than 50 years (equivalent to the lifetime of the connecting cables and casting resin).

In order to utilize EM sensor technology in field application, actual stress measurements on numerous steel cable have been verified in Japan. Here, the actual stress measurements by EM sensor technology on PC bar 13mm, PC wire 7mm and PC strand 37x7mm are compared to measurements by conventional load cell, and the accuracy and reliability of EM sensor measurements are discussed.

3.2.1 PC bar 13mm
Fig. 5 shows the verification of test result of EM sensor measurement on PC bar 13mm. At the beginning of the tensile loading test, the room temperature was 24.1°C. At the maximum tensile load 48.99kN, the EM sensor showed 30.50kN with 0.8% error.

### Fig. 5 Verification of test result of EM sensor measurement on PC bar 13mm

![Graph of Verification of test result of EM sensor measurement on PC bar 13mm](image_url)
3.2.2 PC wire 7mm

Fig. 6 shows the verification of test result of EM sensor measurement on PC wire of 7mm diameter. In the beginning of the tensile loading test, the room temperature was 24.8°C and the EM sensor showed –0.08kN. At the maximum tensile load 30kN, the EM sensor showed 29.03kN with 3.0% error.

![Fig.6 Verification of test result of EM sensor measurement on PC wire 7mm](image)

3.2.3 PC strand 37x7mm

The objective of this test was to verify (i) the reliability of EM sensor actual stress measurement on bundle of wires based on one single wire calibration data (ii) capability of EM sensor actual stress measurement on sheathed strand as expected for NDE innovative technology.

Fig. 7 shows the specimen and loading set up for the multiple wire test. The specimen is 37 of 7mm wires that sheathed with poly-ethylene. To keep tensile force distributed homogeneously, both ends of each 7mm wire are embedded in rectangular parallelepiped concrete blocks symmetrically. Tensile loading is controlled by 2 jacks which are set symmetrically on both ends of the specimen.

By using the incremental permeability versus stress and temperature relationship of single 7mm wire as shown previously, the actual stress of 37x7mm strand is measured and compared to the mean forces of 2 jacks and the verification test result is shown in Fig.8. It was observed that the error is less than 10% (including the elastic deformation due to inadequate stiffness in between two concrete blocks), it is verified that EM sensor is capable of measuring the actual stress on sheathed bundle of wire.

![Fig.7 Specimen of 37 x 7mm strand and loading set up](image)

![Fig.8 Verification test result of EM sensor measurement on PC sheathed strand 37x7mm](image)
4 APPLICATION OF EM SENSOR TECHNOLOGY

4.1 Health monitoring on new PC structure
To verify the on-field application of EM sensor technology on new PC structure to monitor strand stress in I-beams, a field project successfully completed in SD USA is discussed. The purpose of this project was to develop a stress monitoring system for pre-tensioned concrete beam. Fig. 9a shows the cross section of I-beam with 28 FW0.5” 270 grade strands and the location of measured strand. The length of the beam was 60.96m divided into three spans as shown in Fig. 9b. Fig. 10 shows graphically the location of 4 sensors along the measured strand. In order to avoid the possible damage and corrosion during construction and sensors’ service period, a plastic dip was used to cover the steel covering of the sensors. Furthermore, after the sensor was installed on the strand, silicon sealant was used to fill the gap between the strand and the sensor.

The measured results of forces along the strand at various stages of loading history is shown in Table 1 and assessed as follows:
1. The first measured result was taken after the strand was tensioned up to 137.8kN at the temperature of 22.0°C. From the results tabulated in Table 1, it is observed that the stress is homogeneous along the four measured locations. Measured result of Sensor-4 is approximately 5% less than that of applied force. Considering the force applied at the end i.e., 48.77mm away from measuring location, the measured stress value is reasonable.
2. The second measured result was taken 2 hours after the strand was tensioned at the same temperature with the first measurement was taken, showed approximately 0.7% loss in stress.
3. The third measured result was taken 6 days after the strand was tensioned, 4 days after concrete was cast, at the temperature of 27.3°C. Stress loss of 1% to 2% was observed during this loading stage.
4. The fourth measured result was taken after the strand was released as the compressive strength of the concrete reached 8.75ksi. The value obtained from the first sensor showed stress loss to 66.4kN that is about half of the original stress value. This was because the measured location was 0.53m away from the end of beam where the released stress of the strand was zero. It is also seen from the results that there is an increase of about 0.5% to 1% in stress at other three locations even though the strand was released. This is due to the thermal expansion coefficient difference between strand and concrete within 12.1°C temperature change.

<table>
<thead>
<tr>
<th>Loading stage</th>
<th>Sensor</th>
<th>Load cell</th>
<th>S4</th>
<th>S3</th>
<th>S2</th>
<th>S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediately after pre-tensioning</td>
<td>Strand un-released</td>
<td>Concrete un-cast</td>
<td>T=22.0°C</td>
<td>137.8</td>
<td>131.8</td>
<td>131.7</td>
</tr>
<tr>
<td>2 hours after pre-tensioning</td>
<td>Strand un-released</td>
<td>Concrete un-cast</td>
<td>T=22.0°C</td>
<td>–</td>
<td>130.9</td>
<td>131.3</td>
</tr>
<tr>
<td>6 days after pre-tensioning</td>
<td>Strand un-released</td>
<td>4 days after concrete was cast</td>
<td>T=27.3°C</td>
<td>–</td>
<td>128.1</td>
<td>127.3</td>
</tr>
<tr>
<td>30 days after pre-tensioning</td>
<td>Strand released</td>
<td>25 days after concrete was cast</td>
<td>T=15.2°C</td>
<td>–</td>
<td>129.3</td>
<td>127.8</td>
</tr>
</tbody>
</table>
4.2 Health monitoring on existing PC structure

Actual stress determination is one of the problems in the case of health monitoring on existing structures. However, if the elasto-magnetic characteristics of the measured material can be identified, the actual stress of the existing cable can be measured by utilizing EM sensor technology as described in section 2.3.2. To ascertain the application of EM sensor technology on existing PC structure, EM method employed to monitor actual stress in cables at YZ cable stayed bridge in China is discussed. Sensors configuration of stayed cables of the bridge and on site fabricated sensor are shown in Fig.11a and Fig.11b, respectively.
5 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 of steel wires, bars and cables. Therefore, this measurement technology is suitable for developing a health monitoring system for any prestressed concrete (PC) structure.

Some concluding remarks are summarized as follows:
1. EM sensor consists of the input device (magnetizing coil) and the output device (sensing coil). But the real sensor is the ‘intelligent’ PC structure itself that has high magnetic sensitivity to stress.
2. For PC steel, previously calibrated data can be utilized for the PC from the same specification.
3. Scattering in the stress measurement on PC steels is not influenced by the mechanical properties. Successful application of EM technology, knowledge of magnetic characteristics and its scattering is essential. By observing numerous measurement results, it is confirmed that the scattering of elasto-magnetic characteristics is within 5%.
4. Temperature change influences the magnetic properties of steel and the temperature error is up to about 10N/mm² per ℃.
5. EM sensor transfers the stress from the measured element to the sensing coil with the change of the magnetic flux. This phenomenon is not influenced by insulation resistance, however, ferromagnetic surrounding the sensor affects the distribution of the magnetic flux. Therefore, magnetic shielding of the sensor is needed when ferromagnetic surrounding the sensor is not stable.

REFERENCES