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Magnetic Hysteresis based Prestressing Measurement for PSC Bridge Health Monitoring

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ABSTRACT

The EM sensor is based on the elasto-magnetic property under technical magnetic saturation. It consists of a primary coil to magnetize the ferromagnetic material and a secondary coil to measure the induced electromotive force that is directly proportional to the change rate of the applied magnetic field and the relative permeability. Assuming that the magnetic field saturates the ferromagnetic material technically, the tensile force can be estimated by measuring the permeability of the pre-stressing tendon using an EM sensor. To verify the proposed method, the experimental study was performed using down-scaled girder model. The EM sensor was embedded into the down-scaled girder and measured the B-H loop change according to the tensile forces. To quantify the changes in measured data, the area of B-H loop was extracted from measured B-H curve. The area of B-H curve was decreased according to the tensile force increase. Thus the tensile force of PS tendons could be estimated by tracking the signal variation measured by EM sensors.

1. INTRODUCTION

The PSC bridges have been constructed world widely after the first PSC bride was built in 1936. The tensile forces of prestressing tendons are most important factor to maintain the PSC bridges. However, the tensile force of the PS tendon can changed due to many kinds factors including instantaneous losses such as elastic shortening, friction, and anchorage set occurring at the time of transfer of the prestressing force, as well as time dependent losses due to steel relaxation and concrete creep and shrinkage that occur after transferring and during the life of the member. To measure the tensile force of PS tendons, a variety of studies have been researched using fiber optic sensors (Kim et al., 2012) and magnetic sensors (Wang et al., 2005). This research concentrated to find the relation between the iron loss and tensile force and the way to monitor the tensile force of PS tendons using the iron loss measured by the EM (Elasto-Magnetic) sensors.

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2. TENSILE FORCE ESTIMATION USING EM SENSOR

Tensile force measurement using an EM sensor utilizes the adverse effects of this magnetostriction. When an external force is applied to a magnetic body, the magnetic characteristic is changed, and this is called an adverse effect of magnetostriction. If the applied external force is $\sigma$and the direction cosine of the magnetization direction is $(\alpha_1, \alpha_2, \alpha_3)$ and the direction cosine of the external force input direction is $(\beta_1, \beta_2, \beta_3)$, the energy change caused by the external force is as follows;

$$\mathrm{E} = -\frac{3}{2}\lambda_{100}\sigma(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2) - 3\lambda_{111}(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_2\alpha_3\beta_2\beta_3 + \alpha_3\alpha_1\beta_2\beta_1) \tag{1}$$

where $\lambda_{100}$and $\lambda_{111}$are the magnetostriction constant in the [100] axial direction and the [111] axial direction, respectively. Because $\lambda_{100} = \lambda_{111} = \lambda$ in the case of isotropic magnetostriction, Eq. (1) change accordingly (Jin, 2004).

$$\mathrm{E} = -\frac{3}{2}\lambda_{100}\sigma\left(\alpha_1\ \beta_1\ + \alpha_2\ \beta_2\ + \alpha_3\ \beta_3\ \right)^2 = -\frac{3}{2}\lambda\sigma\ cos^2\theta \tag{2}$$

where θ is the angle between magnetization and the external force. Therefore, when stress is applied to a material having magnetostriction, uniaxial anisotropy occurs because of magnetostriction, and the magnetic properties are changed accordingly. Thus, it is possible to measure the tensile force introduced into the PS tendon, that is, the tensional force, by measuring the magnetic properties of the PS tendon.

3. EXPERIMENT USING SCALED PSC GIRDER TO VERIFY THE INFLUENCE OF SHEATH CURVATURE

Experiments were carried out to verify the field applicability using a scaled PSC girder model with an embedded EM sensor.

3.1 Experimental settings

Scaled PSC girders with lengths of 6 m were fabricated, as shown in Fig.1, and tensile force measurement was performed to verify the applicability of the embedded EM sensor. The embedded EM sensors were installed on the left anchorage and maximum eccentric parts of specimen, as shown in red in Fig. 1 and 2. The primary coil (1.2t PEW enamel copper wire) of each sensor was wound approximately 300 turns, and the secondary coil (0.3t PEW enamel copper wire) was wound approximately 120 turns.

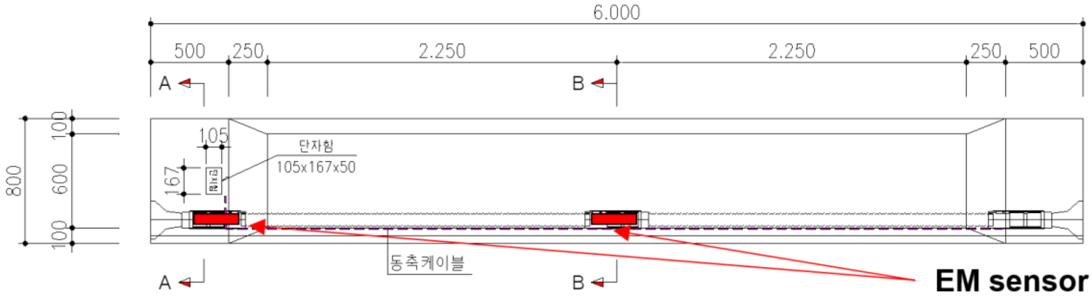


Fig.1 Diagram of scaled PSC girder specimens

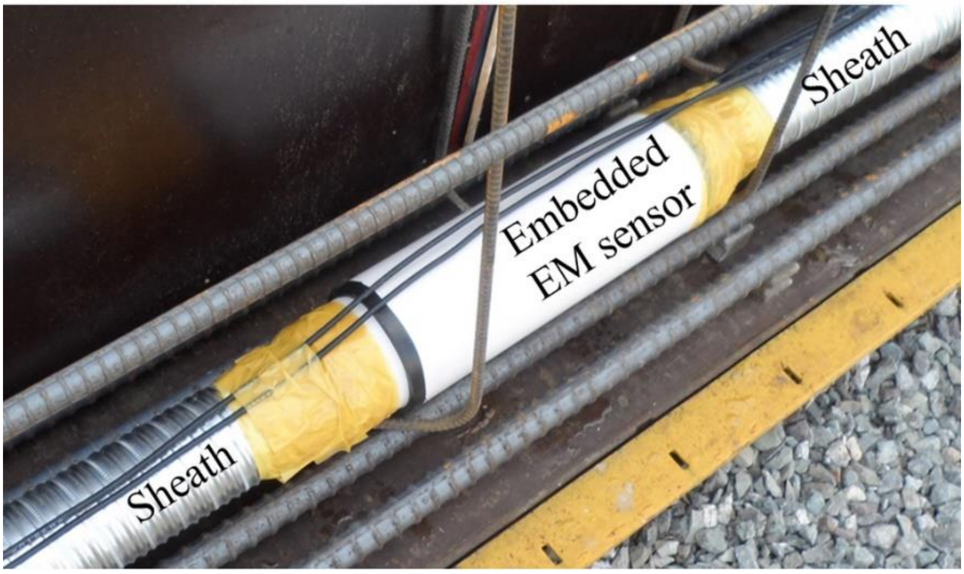
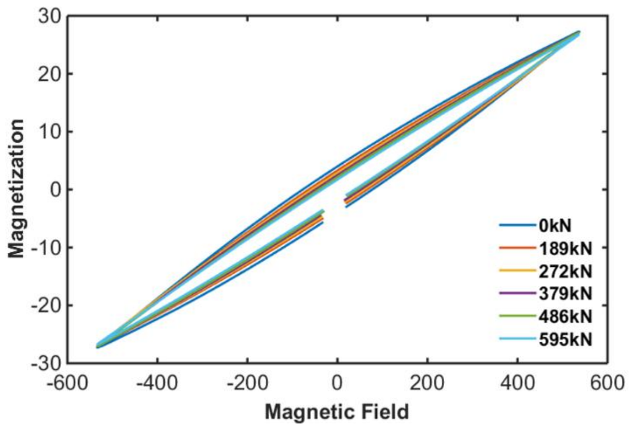


Fig.2 Installation of embedded EM sensor

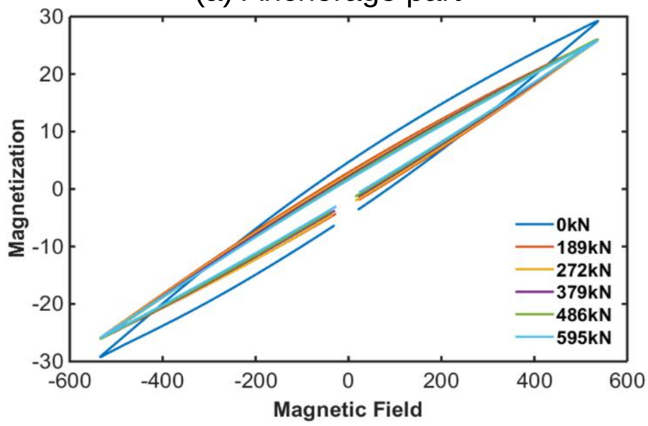
After installation of the embedded EM sensor on the sheath, the sensor cables were taken out of the left end and then the concrete was poured into the specimen. After curing of the concrete, four PS tendons (15.2 mm in diameter, B type, 7-wired) were installed in specimen, and load cells were installed on the left anchorage of each specimen. The tensile force was introduced in five steps (100 to 500 bar according to the pressure gauge of the hydraulic jacking machine). The magnetic hysteresis using the embedded EM sensor and reference tensile force using the load cell were measured at each tensile force step. A power integrator, which involves a power amplifier, integrator, and DAQ, was used to measure the magnetic hysteresis of PS tendons using the embedded EM sensor. The power integrator was designed and manufactured to be applied in the field by reducing measurement time and equipment size. The conventional DC-based measuring instrument used a triangular wave of 0.02 Hz as an input signal, which took about 70 s to measure the hysteresis curve once, whereas the power integrator took about 1 s to measure one time using a sine wave of 1 Hz. The input signal to measure magnetic hysteresis was a ± 3 V, 1-Hz sine wave, and measurements were repeated five times at each tensile force step.

3.2 Result of experiment on scaled PSC girder model

Fig. 3 shows the measurement results of the hysteresis curves of the scaled PSC girder specimen. The magnetic hysteresis curves of the PS tendons could be measured using the embedded EM sensor in the PSC girder, and it was confirmed that the area of the hysteresis curves decreased as the tensile force increased. This suggests that the introduction of stress in the longitudinal direction of the PS tendons prevents them from being magnetized. It was also confirmed that the magnetic hysteresis curves of the PS tendons inside the girders can be measured smoothly using the embedded EM sensor.



(a) Anchorage part



(b) Maximum eccentric part

Fig. 3 Variations in magnetic hysteresis depending on tensile force

The area of hysteresis curves were extracted to quantitatively evaluate the change in magnetic properties caused by the change in tension force. Fig. 4 shows the change in the area of hysteresis with increasing tensile force. The area of magnetic hysteresis curve quantitatively decreased with increasing tensile force, even though the magnetization time was reduced from 70 s to 1 s. Thus, this study used the area of magnetic hysteresis curve as a characteristic factor to estimate the tensile force of PS tendons.

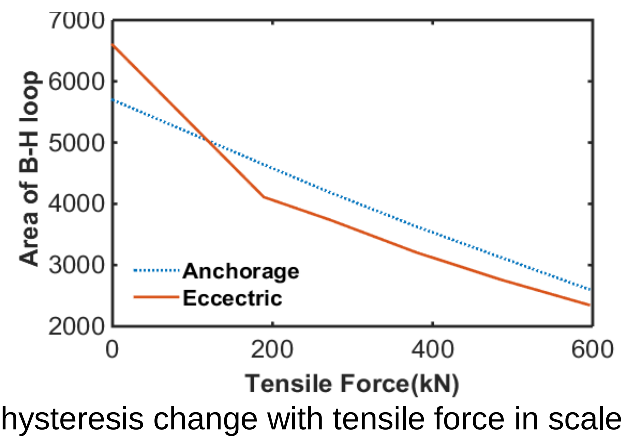


Fig. 4 Area of hysteresis change with tensile force in scaled PSC girder test

Fig. 5 shows the result of regression analysis of the area of hysteresis measured by the sensor of the anchorage part, adjacent to the load cell, and the load cell data to confirm the relationship between the measured tensile force and the area of hysteresis curve.

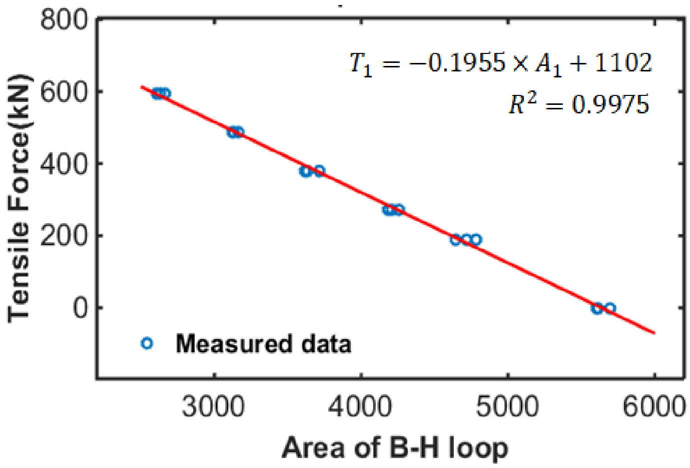


Fig.5 Relationship between area of hysteresis and tensile force in scaled PSC girder test

In the scaled PSC girder test, the area of hysteresis decreased with increasing tensile force. In the specimen, which has a linear sheath, it was possible to obtain a very linear result.

4. CONCLUSIONS

A magnetic hysteresis based tensile force estimation for PSC girders using embedded EM sensor was proposed in this research. The B-H loop of ferromagnetic material is affected by the induced tensile force in the specimen. To validate the proposed method, a scaled PSC girder test was performed using sensor embedded specimen that had 1 sheath line. The embedded EM sensors were installed at the left anchorage parts and at the maximum eccentric part through the sheath before casting concrete. After casting and curing concrete, tensile force was induced in steps, and the B-H loop was measured at every tensile force step. Also, the reference tensile forces were measured from the load cell at the left anchorage of specimen. The B-H loop was varied according to the increase of tensile force. Especially, the area of the B-H loop decreased with tensile force increase. To quantify the area variation the area of B-H loop was extracted and regression analysis was performed to find relationship between area of B-H loop and tensile force. According to the results, the embedded EM sensor can measure the magnetic responses of unrevealed PS tendon even if it located inside of concrete and the tensile force could be estimated based on the variations of area of magnetic hysteresis of the PS tendon using the embedded EM sensors in the field environment.

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