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Magnetostriction Analysis of a Post Tensioning (PT) Tendon System under Varying Tension Forces

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ABSTRACT

It is importance to monitor the tension force of a Post Tensioning (PT) tendon system to ensure the integrity and safety of a pre-stressed concrete structure. Recently a tension force monitoring technique using eddy current measurements is proposed by the authors' group to provide a warning for the excessive loss of PT tendon force. The proposed technique measures the magnetic flux density on the wedge surface at the PT tendon anchor and relates this measurement to the PT tendon force. In this paper, numerical simulations are performed to investigate the variations of the magnetic flux density under different PT tendon force levels. Based on the magnetic material properties evaluated by material property testing, a three dimensional PT tendon model, which consists of a tendon, a wedge, and a barrel, is developed. Then, the relationship between the PT tendon force and the magnetic flux density is examined using ABAQUS 2016. To validate the simulation results, laboratory experiments are performed using a 3.3m long pre-stressing tendon. The experimental results show a great agreement with the simulation results.

1. INTRODUCTION

Advent of pre-stressing method enables to overcome shortcomings of previous reinforced concrete bridges such as limited span length and cracking under service conditions. Due to its structural characteristics, the performance of a PSC bridge depends largely on the state of the pre-stressing tendon (Washier, G.A., 2002). Recently a tension force monitoring technique using eddy current measurements is proposed by the authors' group to provide a warning for the excessive loss of PT tendon force. The proposed technique measures the magnetic flux density on the wedge surface at the PT tendon anchor and relates this measurement to the PT tendon

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force. The advantages of the proposed technique are (1) simple installation, (2) low cost, (3) low power consumption and (4) high durability (Kim. J.M. 2017). In this paper, the developed numerical simulations are performed to investigate the variations of the magnetic flux density under different PT tendon force levels.

2. Analogy of magnetostriction

To estimate the tension force loss from the stress variation on the wedge surface, inverse effect of magnetostriction in ferromagnetic materials is utilized. This effect refers to the reverse phenomenon such that if the ferromagnetic material has any change in size or stress condition, it induces a magnetic field (Jiles, D., 2015).

Since the inverse effect of magnetostriction is not modeled with any of commercial numerical analysis program. In general, magnetostriction is a nonlinear effect, but it can be treated as a linear effect over a certain range of operation. The linear magnetostrictive effect is called Piezomagnetism and is described by the governing equation in Table. 1 (IEEE Std, 1991). There is a strong analogy between piezomagnetism and piezoelectricity. When this analogy is fully exploited, piezomagnetic behavior can be modeled with the piezoelectric analysis.

Table. 1 Comparison of Piezomagnetic and piezoelectric governing equation

Piezo magnetism	Piezoelectricity
$S_{ij} = s^{H}_{ijkl}T_{kl} + d_{kij}H_k$ $B_i = d_{ikl}T_{kl} + \mu^{T}_{ik}H_k$	$S_{ij} = s^{E}_{ijkl}T_{kl} + d_{kij}E_k$ $D_i = d_{ikl}T_{kl} + \epsilon^{T}_{ik}E_k$

3. Numerical simulation of magnetostriction on PT tendon system

A numerical simulation is performed using a finite element analysis software, ABAQUS 2016. In this software, piezoelectric analysis only can be used in elastic condition of materials. However, part of wedge and tendon in PT tendon system are stressed and deformed over the yield point of materials. For applying actual condition of PT tendon system under the pre-stressing, simulation has to process two step. In the first step, the stress and deformation are analyzed by dynamic, implicit procedure. And then, the piezoelectric analysis is performed using the result of the first step.

For simulating an actual PT tendon system, a three dimensional model is structured. The detailed mechanical properties are decided in Table. 2. Also, Magnetic permeability is measured under different stress condition by Material testing system (MTS), and the result is shown in Fig. 1. In the simulation model, the end of tendon is forced 180 kN and then released until 30 kN. The under surface of anchor head is set fixed as same as actual PT tendon system. In the analogous piezo-magnetic boundary condition is to set the magnetic potential equal to zero on top and bottom edges in wedge and anchor head.

Table. 2 Mechanical properties of numerical analysis model

	Anchor head	Wedge	Tendon
Density [ton/mm^3]		7.85E-09	
young's modulus [MPa]	210000	200000	185000
Poisson's ratio	0.3	0.4	0.23
yield stress [MPa]	476	392	1860
tensile stress [MPa]	657	628	2140

plastic elongation	0.2	0.17	0.055

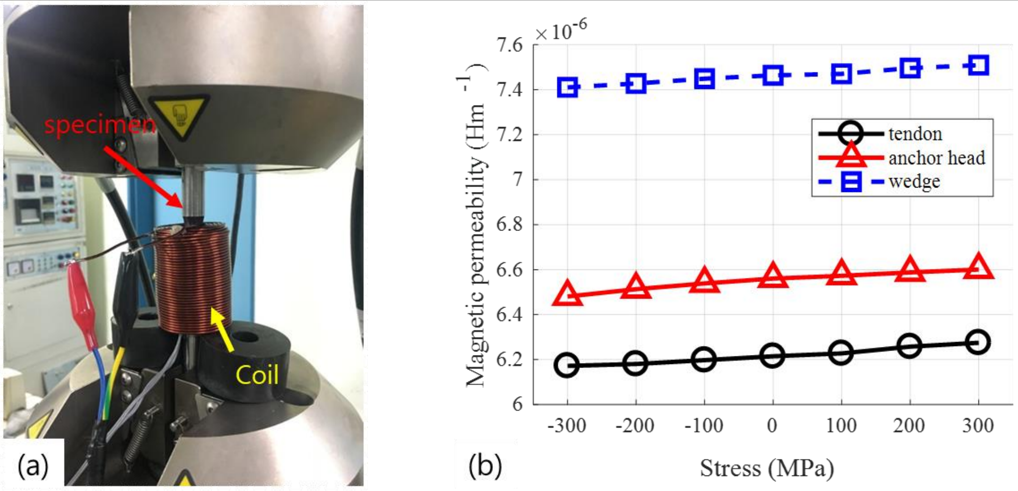

Fig. 1 Magnetic permeability test by MTS (a) Experiment setup,
(b) Result of magnetic permeability under different stress condition

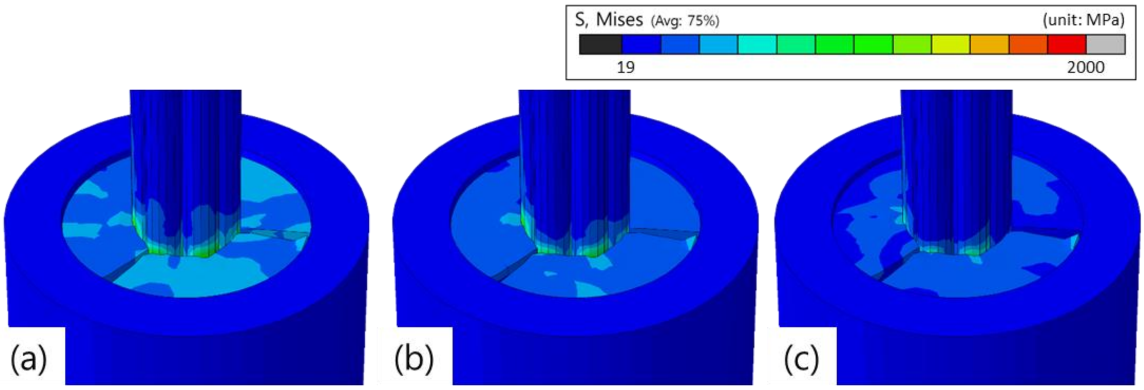

Fig. 2 stress concentration result of PT tendon system (a) 180 kN, (b) 120 kN, (c) 60 kN

Fig. 2 is shown the stress concentration of numerical analysis result of PT tendon system. The stress concentration is occurred at contact point between wedge and tendon. After maximum load, some element of wedge connected tendon or anchor head are excessed the yield stress, so that the plastic behavior is shown in that elements under tensile force loss condition at tendon. When the tensile force is decreased, the stress concentration of wedge surface is also reduced.

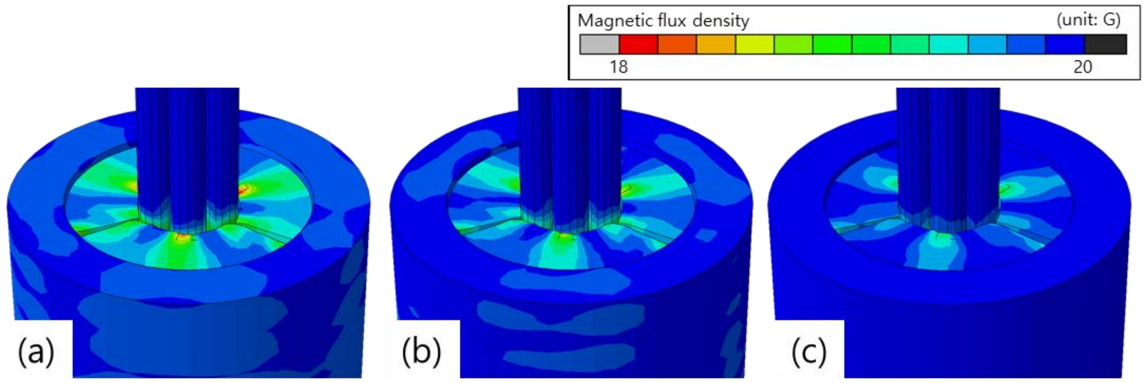

Fig. 3 Magnetic flux result of PT tendon system (a) 180 kN, (b) 120 kN, (c) 60 kN

Fig. 3 is shown the magnetic flux density of numerical analysis result of PT tendon system. The magnetic flux density is inverse proportional to the stress. Therefore, the high stress concentration area at the interface between wedge and tendon is lowest in the surface of PT tendon system. Similar tendency between magnetic flux density and stress distribution, after maximum load at end of tendon, magnetic flux density is gradually increased when the tensile force loosed.

4. Lab Scale Experimental validation

To validate the simulation results, laboratory experiments are performed using a 3.3m long pre-stressing tendon. A mono-tendon was inserted into a steel frame, and the tension is applied to the tendon using a custom-designed universal testing machine, as shown in Fig. 4. To measuring magnetic flux density of wedge surface, eddy current sensor is composed of excitation coil (100 turn coil) and sensing coil (20 turn coil). The tension force of the tendon was increased up to 180 kN initially, and gradually reduced to 30 kN with 30 kN interval. At each force level, magnetic flux density is measured. The specific parameters value of experimental setup is shown in Table. 3.

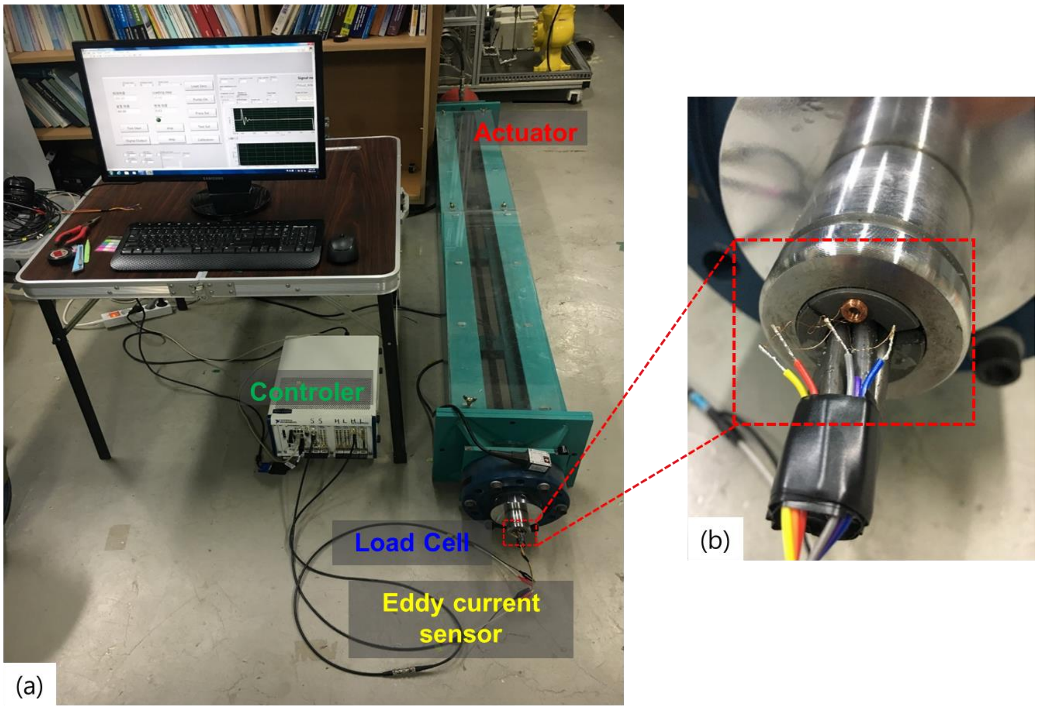

Fig. 4 Experimental setup to measure magnetic flux at PT tendon system

Table. 3 Experimental setup parameters value

Tendon Force Steps	180 kN ~ 30 kN (6 steps)
Strand Type	Φ15.2 mm x 3200 mm
Resistance of Sensor (Drive – Sensing)	0.60 Ω – 3.15 Ω
Inductance of Coil (Drive-Sensing)	1.77 μH – 44.01 μH
Frequency	100 ~ 2,000 MHz
Input Volt.	-2 V ~ 2 V
Sampling frequency	20 MHz
DAQ Time	0.005 sec

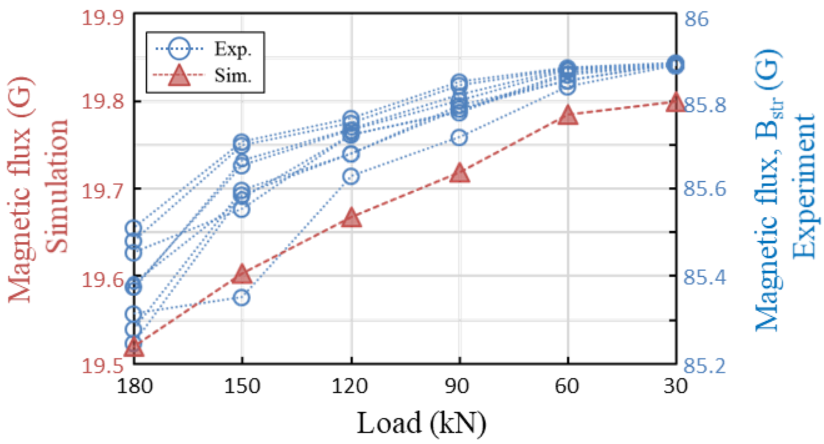

Fig. 5 The comparing magnetic flux result between experiment and numerical analysis

Fig. 5 is the result of magnetic flux at experimental test and numerical analysis.

When the tensile force is reduced, the magnetic flux is gradually increased. By this relation, the experimental results show a great agreement with the simulation results.

5. Conclusion

This paper deals with a numerical analysis of PT tendon system which is presented to predict the magnetic flux density under the different stress condition. Also, to validate the result of numerical analysis, the experimental test is carried out to evaluate tensile force loss of a 3.3 m long pre-stressing tendon. As similar result between numerical and experimental test, the monotonic relationship between tendon force loss and magnetic flux density is successfully observed.

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