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# Field Application of TFC-based Electromagnetic Sensors for Monitoring Cross-sectional Loss in Tendons of Bridges

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ABSTRACT: External tendons in prestressed concrete (PSC) bridges are essential for structural performance and durability. However, internal damage to strands within grouted ducts is difficult to detect through visual inspection. To address this issue, the Korea Institute of Civil Engineering and Building Technology (KICT) developed a non-destructive testing (NDT) sensor based on the Total Flux Change (TFC) principle, derived from Faraday's law of electromagnetic induction. The TFC-based electromagnetic (EM) sensor was designed for field use, featuring a lightweight, detachable frame and wireless data acquisition system. The sensor generates an alternating magnetic field via a primary coil and measures the induced voltage from a secondary coil. A reduction in strand cross-sectional area alters the magnetic flux, resulting in a measurable variation in the induced voltage. Field tests were conducted on the Jeongneungcheon Overpass in Seoul, targeting external tendons between piers. The sensor successfully measured voltage variations along the tendon length. In tendons with suspected damage, the voltage amplitude showed distinguishable reductions, unlike in undamaged control cases. Results were consistent with previous laboratory experiments on specimens with artificially induced strand loss. The findings confirm that the developed EM sensor enables efficient and intuitive detection of internal tendon damage with practical field applicability, even in actual bridge environments. This study demonstrates the feasibility of the TFC-based EM sensor for practical field applications and highlights its potential for integration into long-term bridge monitoring systems.

KEY WORDS: Prestressed concrete bridge; External tendon; Electromagnetic sensor; Total flux change; Non-destructive testing

## 1 INTRODUCTION

Prestressed concrete (PSC) bridges have been widely adopted in modern road bridge due to their advantages in structural safety, aesthetics, serviceability, cost-effectiveness, and ease of maintenance. Among various structural components of PSC bridges, external tendons play a critical role by enhancing structural performance, allowing for flexible prestress control, facilitating maintenance, and providing design versatility.

However, since external tendons contain prestressing strands – typically seven-wire strands – embedded within ducts, it is inherently difficult to directly inspect them for damage during the service life of the structure. A notable example of such a limitation occurred in February 2016 with the failure of an external tendon in the Jeongneungcheon Overpass, constructed in 1999 in Seoul, Korea. The failure was attributed to undetected strand damage caused by grout defects inside the duct, which could not be identified through visual inspection.

Following this incident, the Korea Institute of Civil Engineering and Building Technology (KICT) initiated extensive research to develop non-destructive testing (NDT) sensors capable of detecting internal damage to the strands within the duct. As a result, a novel electromagnetic (EM) sensor based on Faraday's law of electromagnetic induction was developed. This sensor allows for effective detection of cross-sectional losses in the strands embedded within external tendons.

However, many of the existing NDT sensors developed for detecting cross-sectional loss in external tendons face limitations in actual bridge sites. These systems often require complex installation procedures, specialized equipment, and controlled conditions, making them less suitable for field environments. In particular, external tendons located in narrow or elevated areas pose significant challenges for sensor installation and measurement. As such, not only the accuracy of damage detection, but also the workability and field applicability of the sensing system become crucial factors for successful deployment in practice. The aim of this study is to evaluate the field applicability and damage detection performance of the developed EM sensor through field tests on actual PSC bridges.

## 2 PRINCIPLE OF TFC-BASED ELECTROMAGNETIC (EM) SENSOR

### 2.1 *Principle of cross-sectional loss detection*

The EM sensor operates on the principle of electromagnetic induction, as governed by Faraday's law. According to this law, a change in magnetic flux induces an electromotive force (EMF) in a closed loop. The induced voltage $V$ is proportional to the number of coils turns $N$ and the time rate of change of magnetic flux $\Phi$, as expressed in Equation (1):

$$V = -N\frac{d\Phi}{dt} = -N\frac{dBA}{dt} \tag{1}$$

Magnetic flux $\Phi$ is defined as the product of magnetic field strength $B$ and the area $A$ perpendicular to the magnetic field, i.e., $\Phi = B \cdot A$. Therefore, if the magnetic field $B$ remains constant, a reduction in the conductive cross-sectional area $A$ – such as that caused by corrosion or fracture in the tendon – results in a corresponding decrease in the induced voltage $V$.

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Based on this principle, a sensor has been developed to detect cross-sectional loss in prestressing strands located inside the ducts of external tendons. As illustrated in Figure 1, the EM sensor is installed to encircle the tendon duct, and an alternating current (AC) is applied to the 1st coil. As the sensor moves along the tendon, it generates a varying magnetic field that induces eddy currents within the steel strands. These eddy currents, in turn, generate a secondary magnetic field, which is detected by the receiving coil as an induced voltage.

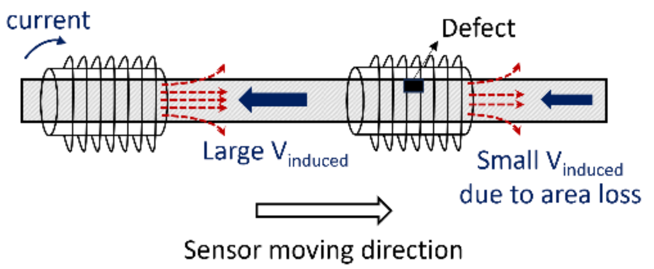


Figure 1. Principle of section loss detect

If there is a cross-sectional loss in the strands, the magnitude of the eddy currents – and thus the induced voltage – decreases compared to undamaged regions. By analyzing the variation in induced voltage, it is possible to identify and localize internal damage to the prestressing strands, even without direct access. This method detects damage based on the change in total magnetic flux, and is referred to as the Total Flux Change (TFC) approach.

### 2.2 *Configuration and features of the TFC-based EM sensor*

To enhance field applicability, the developed TFC-based EM sensor system was designed with an emphasis on lightweight components and low power consumption. The sensor itself adopts a detachable and portable configuration, improving installation efficiency and reducing operational burden in actual bridge environments.

Unlike conventional solenoid-type sensors that require time-consuming on-site winding of wires, the newly developed sensor consists of a separable frame that can be easily mounted and dismounted around the tendon within approximately two minutes. Wheels installed at the front and rear of the sensor enable smooth movement along the tendon surface during scanning.

The sensor consists of a 1st coil that generates an alternating magnetic field, and a 2nd coil located at the center of the sensor that detects the induced voltage via electromagnetic induction. To improve magnetic field concentration and signal sensitivity, eight magnetic cores are embedded within the sensor structure. In order to minimize overall weight, the sensor housing was constructed with a lightweight skeletal frame rather than a solid enclosure. The electromagnetic response of the detachable sensor was verified through COMSOL simulations, showing a distribution pattern comparable to that of conventional solenoid-type sensors.

For accurate detection of the small induced voltage in the 2nd coil, a flat ribbon type cable with a 15-pin D-sub connector was used. This configuration enables the equivalent effect of winding a single wire 15 times, thereby increasing sensitivity. A portable audio amplifier (200 W) was adopted to generate the required alternating current at the desired frequency, avoiding the need for large, heavy power generators typically used in the field. The appearance of the developed EM sensor is shown in Figure 2.

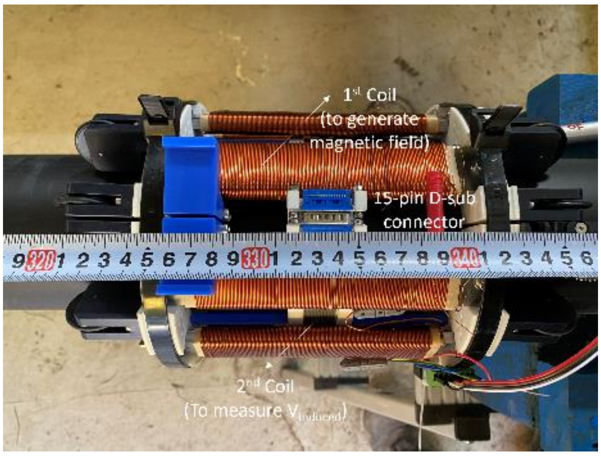


Figure 2. TFC-based EM sensor

The data acquisition (DAQ) system also emphasizes portability and reliability. A microcontroller unit (MCU) was employed to generate sinusoidal signals in the range of 10-40 Hz, which are then amplified by the audio amplifier and supplied to the 1st coil. The induced voltage from the 2nd coil is captured using a high-resolution analog-to-digital conversion board. The MCU wirelessly communicates with a laptop, allowing for real-time monitoring and data acquisition including 1st coil current, 2nd coil voltage, and distance measurements. The entire system is powered by commercial DeWalt rechargeable batteries, enhancing mobility and field usability. The DAQ system and battery pack for field operation of the sensor are shown in Figure 3.

Figure 3. DAQ system and battery of sensor

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# 3 FIELD TEST RESULTS

## *3.1 Overview of Test bridge*

The Jeongneungcheon Overpass, completed in 1999, is located on one of the major expressways for vehicular traffic in Seoul, South Korea. The field tests for detecting cross-sectional loss in prestressing strands were conducted in 2nd section of the bridge. The section is a PSC box girder bridge constructed using a modified MSS (Movable Scaffolding System) method. In this approach, precast panels were assembled on both sides of the box girder to form a three-cell cross section. Both internal and external tendons were used in the prestressing system of this segment. An overview of the structural characteristics of the test section is provided in Table 1, and the appearance of the bridge is shown in Figure 4.

Table 1. Overview of Jeongneungcheon Overpass 2nd Section

| Item | Description |
|---|---|
| Bridge name | Jeongneungcheon Overpass |
| Year | 1999 |
| Design load | DB-24 (43.2 ton) |
| Structural type<br>(Superstructure) | PSC box girder &<br>Steel box girder |
| Length | L=3,500 m<br>(Steel box girder: 1,240 m,<br>PSC box girder: 2,260 m) |
| Width | B=27.0 m |
| Number of lanes | Three lanes per direction |
| Bearing | Pot bearing |
| PSC construction method | MSS |

Figure 4. Jeongneuncheon Overpass Bridge

## *3.2 Target external tendons for NDT*

The nondestructive testing for detecting cross-sectional loss was conducted on external tendons located between Pier 38 and Pier 39 of the bridge. Each span of the bridge includes twelve external tendons, which are installed within the box girder section. Six tendons are positioned on the left side and six on the right side of the PSC box girder, as shown in Figure 5.


Figure 5. PSC box girder of test bridge

Among the tendons on the left side, some tendons were selected for testing due to their accessibility for sensor installation. Each tendon consists of nineteen 15.2 mm diameter seven-wire strands enclosed in a polyethylene (PE) duct filled with grout. The diameter of the duct is 110 mm. An example of the external tendons installed inside the box girder is shown in Figure 6. The testing procedure using the developed EM sensor is illustrated in Figure 7.

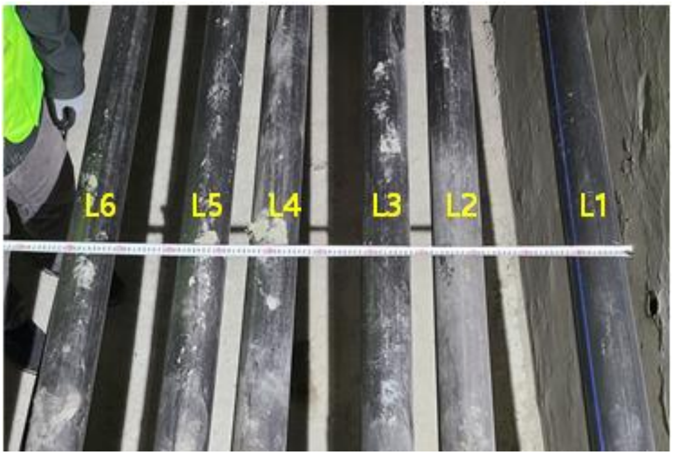


Figure 6. External tendons of test bridge

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(a) Sensor installation (b) Connection of sensor and cable
(c) Connection of cable and wireless DAQ (d) Sensor connection check
(e) Measurement offset setup (f) NDT controll s/w operation
(g) Moving a sensor for NDT (h) NDT result check on site

Figure 7. NDT process of TFC-based EM sensor

### 3.3 *Test results*

The NDT results for three external tendons of the Jeongneungcheon Overpass are shown in Figure 8, represented by the blue, green, and red solid lines. The plotted data correspond to the amplitude of the induced voltage measured by the sensor, after noise removal and mean value subtraction.

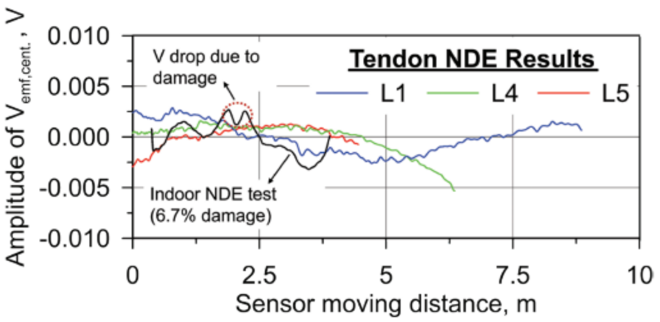


Figure 8. NDT results of TFC-based EM sensor

Among the tested tendons, L4 and L5 were replacement tendons installed after the external tendon rupture incident that occurred in 2016. Therefore, these tendons are presumed to be free from significant strand damage. Although the induced voltage did not appear completely flat along the sensor travel distance—due to surface contamination, variations in the operator's walking speed, and electromagnetic interference from adjacent tendons—no distinct voltage drops were observed in these two cases.

In contrast, the response differed clearly from that observed in a controlled laboratory experiment conducted in 2023, where a tendon specimen with artificially introduced cross-sectional damage was tested. In the laboratory specimen with a 6.7% section loss (simulated by grinding the strand surface), a distinct decrease in the induced voltage amplitude was observed at the damaged location.

These results demonstrate that the EM sensor developed by KICT enables intuitive detection of cross-sectional loss in prestressing strands while maintaining sufficient workability for practical use in actual bridge environments.

## 4 CONCLUSIONS

This study presented the development and field application of a TFC-based EM sensor designed to detect cross-sectional loss in prestressing strands within external tendons of PSC bridges.

The sensor, developed based on Faraday's law of electromagnetic induction, demonstrated reliable performance in identifying potential damage zones by measuring changes in induced voltage. Field tests conducted on the Jeongneungcheon Overpass confirmed that the sensor could detect localized cross-sectional loss with clearly distinguishable signal behavior, even under the practical constraints of real bridge environments.

Compared to conventional solenoid-type sensors, the developed system significantly improved field applicability by introducing a lightweight, detachable design, wireless data acquisition, and low-power operation. These features enabled quick installation and stable measurement, proving the sensor's practicality for on-site inspections.

Future research will focus on further quantifying damage levels, validating the sensor performance under various damage conditions, and expanding its application to other bridge types and tendon layouts. Long-term monitoring and integration with digital maintenance platforms are also potential areas for future development. These findings highlight the potential of the TFC-based EM sensor as a practical and scalable solution for non-destructive inspection of PSC bridges.

## ACKNOWLEDGMENTS

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