Performance Evaluation on Core Wire of Smart Strand for PSC Structures

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ABSTRACT

The Korea Institute of Construction Technology is undertaking the development of the smart strand for PSC structures enabling to measure the prestress force all along its service life since the completion of construction. Apart from such measurement function, the smart strand shall at first satisfy the structural performance required as a tendon. Therefore, research has been implemented so as to embed the sensor within the small diameter of the core wire by using optical fibre sensor. To that goal, new materials were devised for the core wire to avoid the method cutting and machining the conventional steel core wire. The performances of the core wire fabricated by this new approach as well as its fabricability and structural performance were examined through tensile test to derive the optimal fabrication method of the smart strand. The tests conducted on the core wire fabricated by the so-selected fabrication method and embedded with the optical fibre sensor revealed that the resulting strain measurement range was significantly larger than the range complying with the design prestress force of the conventional steel strand. The core wire for the smart strand under development was seen to provide sufficient measurement performance as well as to satisfy the required structural performance. Accordingly, the newly developed core wire can be conveniently applied in the conventional steel strand.

KEYWORDS : *PSC, strand, core wire, optical fibre sensor.*

INTRODUCTION

Research dedicated to apply optical fibre sensor for measurement purpose has been and continues to be actively performed [1,2]. Optical fibre was initially developed as a signal transmission device in the field of telecommunications and started to be used for structural monitoring in 1990s with the first application of the optical fibre sensor for the monitoring of Beddington Trail Bridge, Canada, in 1993 [3]. Recently, research results were reported on the application of the optical fibre sensor in PSC structures [4-6]. The Korea Institute of Construction Technology also implemented the development of the smart strand, an innovative strand enabling measurement by using such optical fibre sensor [7].

The strand considered in this study is the 7-wire strand with tensile strength of 1860 MPa usually adopted to introduce prestressing in PSC structures. Figure 1 illustrates the shape and dimensions of the strand. Since the 6 helical wires of the strand are exposed, need is to drive a groove longitudinally to embed the sensor in the helical wire. This solution presents the problem of being easily unable to perform measurement due to various reasons like the exposure to shocks and the damage of the epoxy resin used to fix the sensor. Moreover, the helical wires are shaped like springs inserted with the core wire and are thus not arranged longitudinally. This means that fixing the sensor on the helical wires is not recommendable. Following, the optimal solution would be to install the sensor in the core wire so as to dispose the sensor longitudinally without distortion and to protect it by the helical wires against external damage. However, this alternative is difficult to realize using conventional electrical-resistance sensors due to the very small diameter of the core wire which runs around 5.2 mm. In addition, considering that the PSC bridge is generally longer than 20 m and assuming that electrical-resistance sensors can be used, the difficulty remains due to the high risk of damage following the installation of the lead line on which the sensor is bonded along the length of the bridge. Accordingly, this study selects the thin and filiform optical fibre sensor as the sensor to be embedded inside the core wire of the strand and, conceives various methods enabling its embedment.

Prototypes were fabricated for each of these methods and the corresponding performances were examined by means of tensile tests. The test results were then used to derive the optimal fabrication method. The so-selected optimal fabrication method was applied to fabricate a core wire specimen embedded with optical fibre sensor so as to verify its applicability as a strand and its measurement performance.

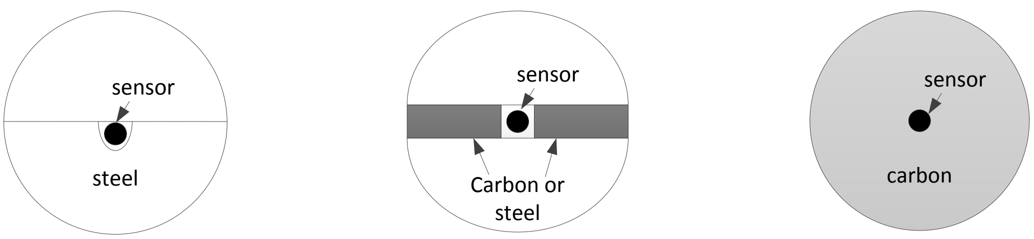
(a) Overall shape (b) Dimensions

Figure 1: Structure of the considered 7-wire strand

1 FABRICATION OF CORE WIRE PROTOTYPES

Since the core wire to be used in the smart strand must afford the embedment of the optical fibre sensor, possible methods are the machining the steel core wire of the conventional strand or the adoption of a totally different fabrication method for the core wire itself. This study considers one method cutting the steel core wire longitudinally and one method fabricating separately the core wire using carbon fibre. The first method was realized by applying water jet for the longitudinal cutting of the core wire. In order to deal with the inherent cross sectional damage caused by cutting, methods were devised to strengthen the cut end by fabricating separately a steel plate and a carbon plate with width and diameter identical to those of the core wire. For the method intending to fabricate separately the core wire, need is to select a material exhibiting stiffness and strength comparable to those of the conventional steel core wire. This material appeared to be carbon fibre satisfying such performance.

Among the methods fabricating the core wire using carbon fibre, the pultrusion method and the braidtrusion method known to be advantageous for the production of circular products while enabling high content in fibre were applied to increase the performances of the core wire. Figure 2 shows the conceptual drawings of the core wire corresponding to each of the devised methods. Table 1 arranges the characteristics of these core wire prototypes. Figure 3 presents the photographs of the core wire prototypes fabricated by each of the considered methods.



(a) by cutting (b) by reinforcing after cutting (c) by fabrication using carbon

Figure 2: Conceptual drawings of the conceived core wires

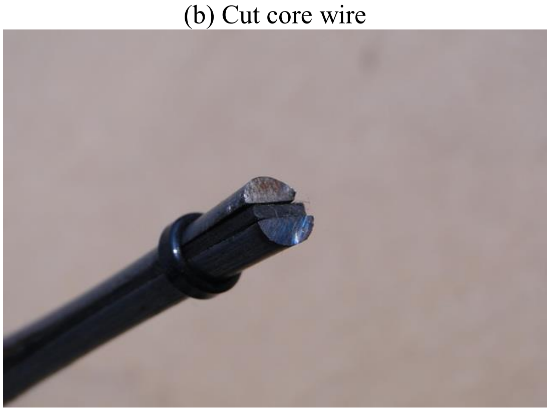
Table 1: Characteristics of the core wire prototypes.

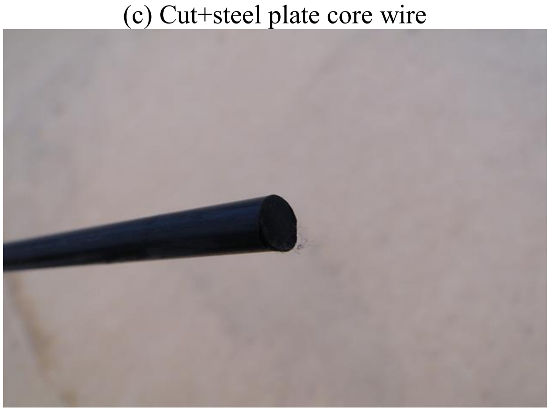
Type of core wire	Materials	Diameter (mm)	Features
Conventional steel	Steel	5.2	Commercial product
Cut	Steel	4.4 – 4.6	Longitudinal cutting
Cut+steel plate	Steel	5.2 – 5.4	Cutting+0.8 mm steel plate
Cut+carbon plate	Steel, CFRP	5.6 – 5.8	Cutting+1.2 mm CFRP plate
Pultruded carbon	CFRP	5.3	Replacement
Braidtruded carbon	CFRP	5.3	Replacement


(a) Conventional steel core wire


(b) Cut core wire


(c) Cut+steel plate core wire


(d) Cut+carbon plate core wire


(e) Pultruded core wire

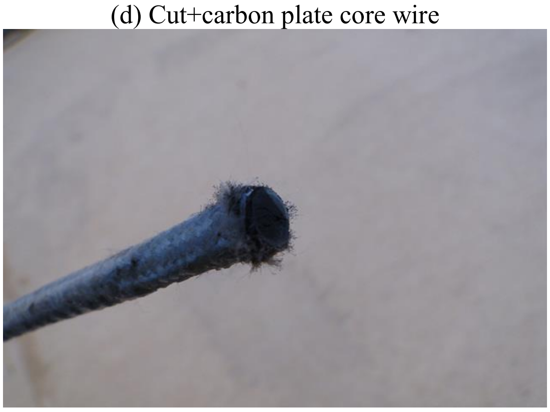

(f) Braidtruded core wire

Figure 3: Conceived core wire prototypes

(a) Coating for improving the adhesion (b) Completed specimens

Figure 4: Fabrication of carbon core wire specimens

The presence of grips is necessary to fix the fabricated specimens to the actuator for the tensile tests. The steel core wire can be fixed as it is to the hydraulic grip of the Universal Testing Machine (UTM). However, the carbon core wire is likely to experience crushing at the grip. Therefore, test was conducted using a specially fabricated device after machining of the carbon core wire. To that goal, the extremities of the specimens were split and coated to increase the bonding force and prevent the occurrence of slip at the anchorage. Thereafter, the coated ends were inserted inside 200 mm-long steel tubes and monolithically fixed by placing mortar to complete the specimens. Moreover, the effective length of the tendon excluding the sleeve was set to be larger than 40D in compliance with CAN/CSA S806-02 (CSA, 2002) [8]. Figure 4 illustrates the fabrication process of the carbon core wire specimens.

2 Test of Core Wire Prototypes and Selection of Optimal Fabrication Method

Figure 5 pictures the test of the conventional steel core wire, cut core wire, cut+steel plate core wire and cut+carbon plate core wire specimens. Figure 6 shows the test of the pultruded carbon core wire and braidtruded carbon core wire specimens.

Figure 5: Test of specimens – 1

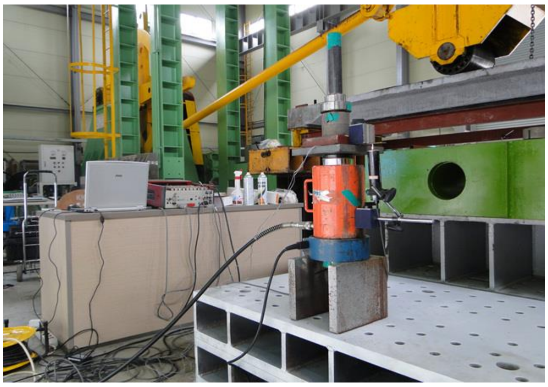
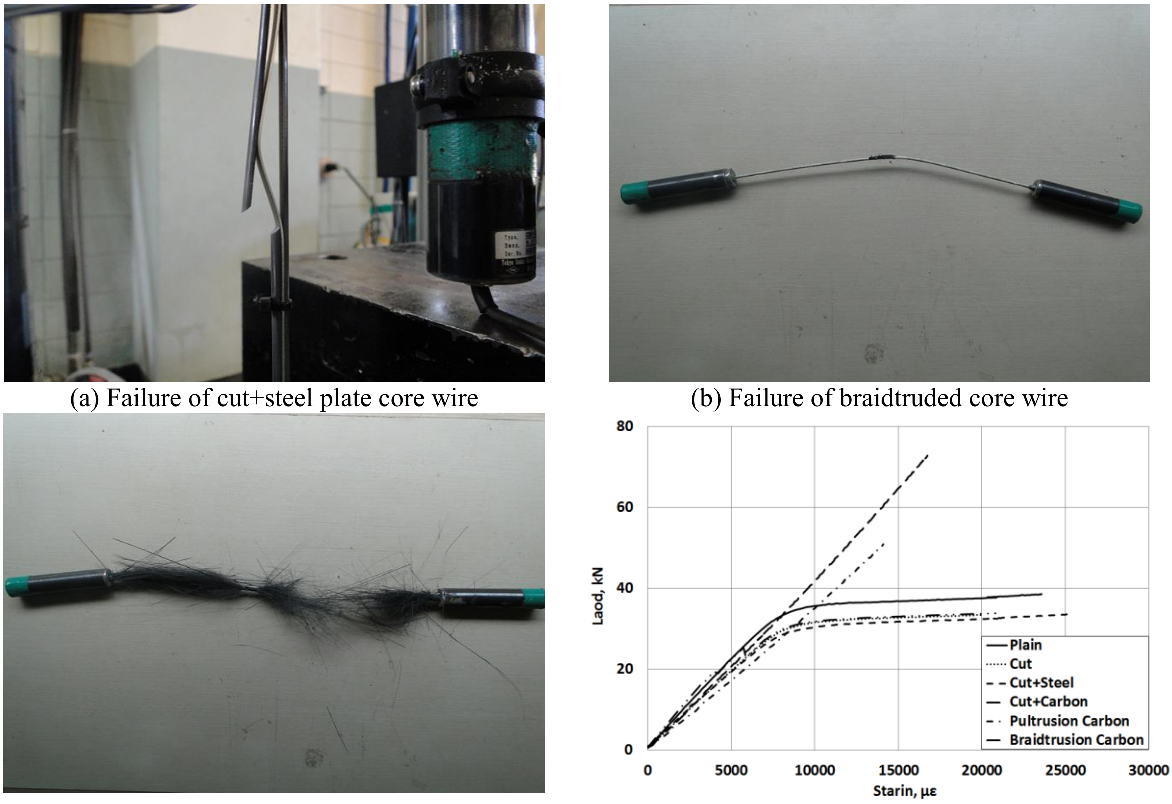


Figure 6: Test of specimens – 2

Electrical-resistance strain sensors were installed on both sides at the centre of each specimen and loading was conducted through displacement control. Failure occurred mainly at the grip for the conventional steel core wire. For the cut+carbon plate core wire, crushing occurred at the grip in the case of high grip pressure while slip occurred in the case of low grip pressure making it difficult to secure correct results until full performance was developed. Besides, for the cut+steel plate core wire and carbon core wire specimens, failure occurred mostly at the centre of the specimens. Figure 7 illustrates typical failure patterns and plots the test results.



(a) Failure of cut+steel plate core wire

(b) Failure of braidtruded core wire

(c) Failure of pultruded core wire

(d) Load-strain curves

Figure 7: Core wire test results

In view of the test results of the specimens, the core wire of the conventional steel strand (Plain) exhibited the largest stiffness within the elastic region. The largest failure load was observed for the carbon core wire owing to pultrusion. Due to the sectional loss caused by cutting, the cut core wire showed lower performance than the conventional core wire in terms of the stiffness and strength. The cut+steel plate core wire developed performances comparable to the conventional steel strand but requires slightly higher fabrication cost due to the necessity of an additional processing for the embedment of the optical fibre sensor. Following, the carbon core wire is selected for the smart strand owing to the development of appropriate stiffness and sufficient strength and, to the ease in the embedment of the optical fibre sensor. However, despite of the better performances developed by the pultruded core wire compared to the braidtruded core wire, the pultruded core wire was seen to be prone to galvanic corrosion at the interface with the external helical steel wires. Accordingly, the braidtruded carbon core wire was finally selected as the optimal fabrication method for the core wire of the smart strand regard to its sufficient strength even if it develops slightly lower stiffness than the conventional core wire.

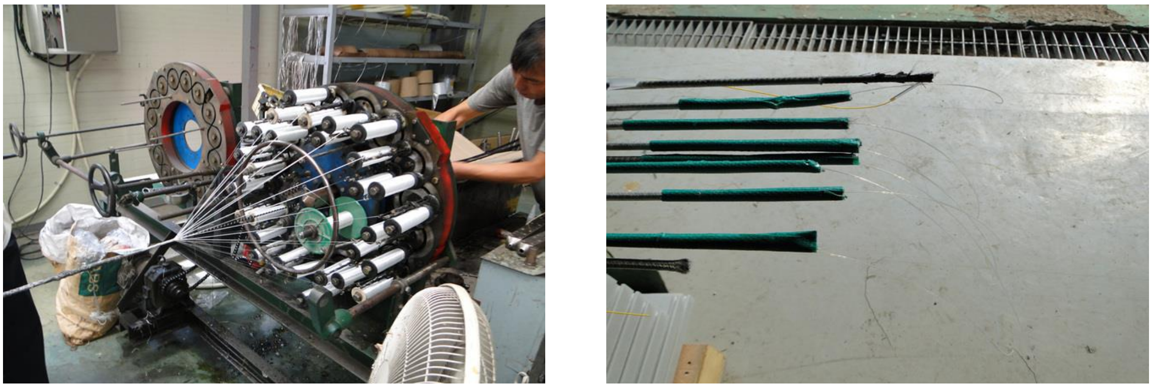
3 Fabrication of Core Wire for Smart Strand with Built-in Optical Fibre Sensor

Since the optical fibre sensor to be embedded in the core wire of the smart strand is made of pure quartz, the sensor is free from corrosion and is advantageous for long-term monitoring thanks to its high durability. Moreover, the optical fibre sensor has been reported to provide higher durability to fatigue compared to the electrical-resistance strain sensor [9]. Since this sensor exhibits also electromagnetic neutrality, it is practically insensitive to the neighbouring electromagnetic waves. This means that the optical fibre sensor provides very reliable measurements. Table 2 arranges the standard specifications of the Fibre Bragg Grating (FBG) sensor embedded in the core wire of the smart strand.

Table 2: Characteristics of optical fibre sensor.

Sensor	Standard specifications	Remarks
Bare FBG sensor	• Strain range : 10,000με • Pigtail length : 1 m • Possibility of Fusion splicing • Wavelength : 1510–1590 nm	• Micro-fibre type • For strain measurement

For the braidtruded carbon core wire embedded with the optical fibre sensor, the carbon fibre is passed through the shaping mold in a non-hardened state after having been impregnated with resin. The circular shape is achieved by wrapping through the squeeze-like rotation of the thin nylon fibre yarns. During the fabrication of the core wire, attention should be paid to avoid any damage of the part installed with the sensor as well as the whole portion diffusing light. The sensor shall be installed inside the carbon core wire to permit adequate measurement of the strain. Moreover, the optical fibre shall be positioned at the centre of the core wire to ease its extraction. Figure 8 depicts the fabrication of the core wire by braidtrusion.



(a) Braidtrusion (b) Completed built-in optical fibre sensor specimens

Figure 8: Fabrication of core wire embedded with optical fibre sensor

4 TEST OF CORE WIRE FOR SMART STRAND WITH BUILT-IN OPTICAL FIBRE SENSOR

The tests for the core wire of the smart strand built-in with the optical fibre sensor were carried out according to the methods depicted in Figures 4 and 6. In addition, two separate systems were provided to measure the optical fibre sensor and to measure the electrical-resistance sensor. Figure 9 shows the test of the prototype and a typical failure pattern.

The failure load of each prototype ranged between 49 kN and 51 kN, indicating that the performance of the prototypes was practically constant. Since the failure load is larger by about 29 to 34% than that of the conventional steel core wire, the proposed core wire can be sufficiently applied to substitute the conventional steel core wire in terms of its performance. Failure occurred with larger load after maintaining a linear behaviour without ductile behaviour. This failure pattern is identical to the typical failure pattern of FRP.

(a) Prototype (b) Failure of prototype

Figure 9: Test and failure of core wire embedded with optical fibre sensor

Figure 10 compares the measurements obtained by the optical fibre sensor and the electrical-resistance strain sensor in each prototype. The values measured by both sensors in all the prototypes are similar on the whole range until failure. The strain measured by the optical fibre sensor reached also values up to 13,000 – 14,000με. The optical fibre sensor is thus able to measure strains significantly larger than 7,500με corresponding to the strain of the strand prestressed up to the allowance of the design specifications of PSC bridge. Accordingly, the optical fibre sensor can be seen as having sufficient applicability.

Figure 11 compares the load-strain curves measured by the optical fibre sensor embedded in each prototype and the strain sensor bonded externally to the conventional steel core wire (Plain). Here, it can be seen that the carbon fibre core wire develops slightly lower stiffness than the conventional steel core wire. Besides, the final failure strength appears to be significantly higher. Since the carbon core wire is assembled with the helical steel wires when applied in real steel strand, the problems caused by this slightly lower stiffness will not have particular effect on the whole performance of the smart strand.

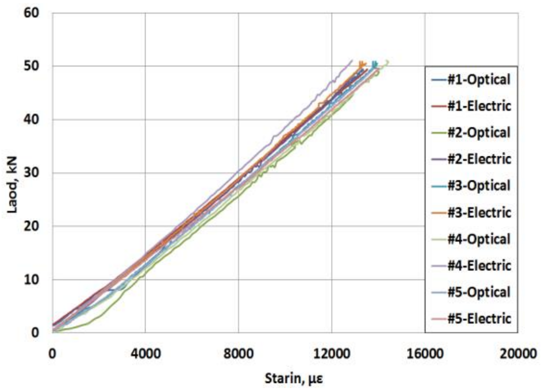


Figure 10: Comparison of load-strain curves measured by optical fibre sensor and electrical-resistance sensor

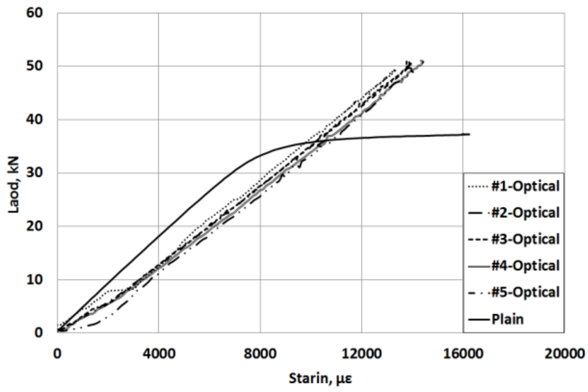


Figure 11: Comparison of load-strain curves measured in conventional steel core wire and carbon core wire

CONCLUSION

In order to develop a core wire for the smart strand enabling to measure the prestress force in PSC structures from the introduction of prestress to the dismantlement, this study examined the method machining the steel core wire after cutting of the core wire and the method replacing the core wire by fabricating the core wire using a completely different material. The method cutting and machining the conventional core wire was excluded from the development process after verification of the performance in which various problems were found out like the fabricability and fabrication cost, as well as the structural performance of the core wire itself. In the case of the carbon core wire developed to replace the conventional steel core wire, the braidtrusion was selected as the optimal fabrication method considering the fabricability and structural performance. Tensile test was then conducted on the carbon core wire embedded with optical fibre sensor and fabricated by braidtrusion. The test results revealed that the so-fabricated core wire secured a measurement range larger than 13,000με, which is significantly larger by more than 173% than the strain of 7,500με required when introducing the design prestress force of the steel strand. Moreover, the tensile strength was also seen to be larger by 29 to 34% than that of the conventional steel core wire. This result indicates that the proposed core wire secures sufficient structural performance. Accordingly, it can be stated that the carbon core wire developed in this study bears sufficient applicability as core wire to be used in the smart strand that will replace the conventional 1860 MPa steel strand.

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