Use of CFCC Tendons and Reinforcements
in Concrete Structures for Durability

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ABSTRACT

This paper presents a brief description of the development, usage, and application of non-corrosive Carbon fiber composite cable (CFCC). In addition to that, case studies of the use of CFCC in bridges are discussed to share the technical information about the successful deployment and various applications of the CFCC tendons and reinforcements. CFCC has already been used as reinforcing materials for more than 140 structures. So far, it is a proven fact that durability of prestressed concrete bridge using CFCC tendons is more than 23 years through harsh environmental conditions, without any deterioration.

KEYWORD

carbon fiber reinforced polymer, durability, non-corroding, prestressed, precast concrete
1. INTRODUCTION

Durable and sustained bridges play an important role in the socio-economic development of a nation. The reinforced concrete bridges need continuous maintenance and attention because of percolation of water, salt-induced decay, etc. in the concrete, and corrosion in the steel reinforcement which causes early deterioration. Replacement of conventional steel reinforcement with non-corroding fiber-reinforced polymer (FRP) reinforcement is one way to eliminate corrosion. Carbon fiber composite cable (CFCC) and the anchoring devices that are being used at the end of the cable were developed by the authors 25 years ago. These authors also developed the manufacturing technology of CFCC for stirrups of concrete bridges. As compared with steel materials, CFCC offers significant advantages especially when used in corrosive environments such as places where damages due to deicing salts and acid of hot spring ambience. It was investigated that CFCC can be used as tendons, reinforcing bars and stirrups for precast beams of prestressed concrete bridges. As of today, CFCC has already been used as the reinforcing material for more than 130 structures. Especially, it is a fact that durability of prestressed concrete bridge using CFCC tendons is more than 20 years, without any deterioration. Due to this reason, CFCC is now expected to be used as the radical measures to solve the problems of early deterioration of conventional prestressed concrete bridges.

2. FEATURE OF CFCC

CFCC stands for carbon fiber composite cables. CFCC is made up of stranded carbon fiber reinforcement polymer (CFRP). The basic configurations of CFCC are shown in Fig. 1.

2.1 Basic Materials and Configuration

CFCC consists of PAN (polyacrylonitrile) based continuous carbon fibers, epoxy resins as binding material and protective wrapping material. PAN based carbon fibers are formed by carbonization of acrylic fibers with high-temperature. Binding material (matrix resin) is a denatured epoxy resin. Wrapping materials include polyester fibers.

Basic configurations of CFCC are available in four types: Rod, 7-strand, 19-strand and 37-strand. Cross sections and designations for single CFCC are shown in Table 1.

<table>
<thead>
<tr>
<th>Strand configuration of CFCC</th>
<th>Designation</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod</td>
<td>U</td>
<td>O</td>
</tr>
<tr>
<td>7-strand</td>
<td>1 × 7</td>
<td></td>
</tr>
<tr>
<td>19-strand</td>
<td>1 × 19</td>
<td></td>
</tr>
<tr>
<td>37-strand</td>
<td>1 × 37</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Advantages of CFCC

CFCC has general properties of CFRP (carbon fiber reinforced polymer) and also configuration properties of stranded wire. Therefore, CFCC has the following advantages over conventional steel strands or other FRP (fiber reinforced polymer) rods [1].

- Excellent corrosion resistance: High acid resistance and alkali resistance.
- Light weight: About 1/5th of the weight of steel with specific gravity of 1.5.
- Low relaxation loss: Relaxation performance of CFCC is nearly same as low relaxation steel strands.
- High tensile strength: Equal to that of steel strand.
- High tensile elastic modulus: Similar to that of steel strands.
- High tensile fatigue performance: Fatigue performance of CFCC is superior to that of the steel strands.
- Low linear expansion: Coefficient of linear expansion is about 1/20 of that of steel.
- Non magnetic interact: No magnetic effect.
- Flexibility: Stranded configuration of the cables allows them to be easily coiled. In addition, CFCC strands can be wound on a reel for easy transportation even if the material is CFRP and the length exceeds 1,000 m.

Fig.1 Basic configuration of CFCC
2.3 Mechanical properties of CFCC
The following section provides a brief description of the basic mechanical properties when CFCC is used for tendons and reinforcing components in prestressed concrete bridges. It is believed that CFCC with these characteristics is most suitable for the tendons and reinforcement materials of prestressed concrete bridges than any other types of FRP.

(1) Load – Elongation curve
The relation between tensile load and elongation of CFCC is shown in Fig. 2. For sake of comparison, cases of steel strands and aramid FRP (AFRP) rod of almost same diameter (0.5") are also presented in Fig. 2. FRP material in CFCC indicates an elastic behavior in all sections up to the point of breakage, and almost no plastic region was observed. It can be noticed from the figure that elastic modulus of CFCC is high as compared with an AFRP rod, rather close to steel materials.

Fig. 2 Load-Elongation curve

(2) Relaxation
Results given by Enomoto et al. [2] for relaxation testing of CFCC 1x7, 12.5 mm are shown in Fig. 3. It is observed that the relaxation property of CFCC is almost the same as that of steel strands. Fig. 3 shows relaxation rate up to 30,000 hours when initial load of 70% of tensile product standard load is applied. Plot gives details of the relation between time and relaxation rate. Relaxation is estimated by the following formula.

\[ Y = 0.056 + 0.396 \log T \]  

where,
\[ Y \]: the relaxation rate (%)
\[ T \]: the time (hours)

Relaxation value after 1,000,000 hours (about 104 years) estimated from this approximation formula is about 2.4%.

Fig. 3 Relaxation curve of the 33,000-hour

(3) Development length
Transfer length of CFCC is the length required to achieve anchoring bond between the CFCC tendon and concrete in prestressed member. It is defined in the “Recommended Guidelines for Design and Construction of Prestressed Concrete Highway Bridge using FRP Tendons” (Public Works Institute of the Ministry of Construction) [3], as 65 times the nominal diameter of the CFCC. Bond strength of CFCC is similar to or greater than that of prestressing steel strands, and several reports have indicated that the required length for bonding is 50 times the nominal diameter or less. However, the Highway Bridge Specification for the development length as 65 times the diameter has been followed here.

(4) Bond strength with concrete
A graphic representation of the test setup for bond strength is shown in Fig. 4. Results from the testing of three specimens confirm that CFCC has sufficient bond strength, with 7-strand 12.5 mm dia. Such CFCC strands have an extraction load of 723 N/cm² in contrast to 7-strand 12.4 mm dia. steel strands having an extraction load of 285 N/cm².

Fig. 4 Test method for bond strength
3. REINFORCEMENT FOR CONCRETE

3.1 Standard Specifications of CFCC
Standard specifications for the configuration of 1-strand, 7-strand, 19-strand and 37-strand is presented in Table 2. Diameter of strand varies from 5 millimeters to 40 millimeters with tensile breaking load from 38 kN to 1,200 kN. Multiple strands are also available for greater tensile load.

3.2 Related Products of CFCC
CFCC can be processed to various shapes in the factory. In addition to use as a tendon and linear reinforcing member (rebars), there are CFCC products that can be used as stirrups and grids, which are also used as the reinforcing materials for concrete structures. Stirrups can be manufactured in predetermined shapes in the factory. Fig. 8 shows one example. In case of grid bar, CFCC wound on reel or coil can be drawn out and cut in specific length, and fabricated as desired shape of grid at work site. It can also be fabricated at factory if its final size is available for transportation.

4. ANCHORING SYSTEM OF CABLE ENDS
When tendon and structural cable are used as prestressed and post-tensioned reinforcements, a tool is required to clamp the CFCC cable at the end. There are two types of anchor fixing methods for CFCC as shown in Fig. 9. One of them is a filling bond method and the other is a wedge method with buffer material.

![Fig. 8 CFCC stirrups of various shapes](image1)

![Fixing method of CFCC](image2)

Table 2

<table>
<thead>
<tr>
<th>Designation (Configuration diameter)</th>
<th>Diameter (mm)</th>
<th>Effective cross sectional area (mm²)</th>
<th>Guaranteed breaking load (kN)</th>
<th>Nominal mass density (g/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>5.0φ</td>
<td>5</td>
<td>15.2</td>
<td>38</td>
</tr>
<tr>
<td>7-strand</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1×7</td>
<td>7.5φ</td>
<td>7.5</td>
<td>31.1</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>10.5φ</td>
<td>10.5</td>
<td>57.8</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>12.5φ</td>
<td>12.5</td>
<td>76</td>
<td>184</td>
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<tr>
<td></td>
<td>15.2φ</td>
<td>15.2</td>
<td>115.6</td>
<td>270</td>
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<td></td>
<td>17.2φ</td>
<td>17.2</td>
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<td>19-strand</td>
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<td>20.5φ</td>
<td>20.5</td>
<td>206.2</td>
<td>316</td>
</tr>
<tr>
<td></td>
<td>25.5φ</td>
<td>25.5</td>
<td>304.7</td>
<td>467</td>
</tr>
<tr>
<td></td>
<td>28.5φ</td>
<td>28.5</td>
<td>401</td>
<td>594</td>
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<td>37-strand</td>
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<td></td>
<td>35.5φ</td>
<td>35.5</td>
<td>591.2</td>
<td>841</td>
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<td></td>
<td>40.0φ</td>
<td>40.0</td>
<td>779.4</td>
<td>1,200</td>
</tr>
</tbody>
</table>
4.1 Filling bond method
Typical Highly Expansive Material (HEM) filling type is shown in Fig. 10 which was cited in Harada et al. [4]. The procedure can be summarized as follows: (1) CFCC is inserted into steel sleeve with screw-threads, (2) Highly Expansive Material is filled into the sleeve, and (3) it is anchored by nut. Tensioning/anchoring work sequence which uses this HEM filling type device is shown in Figure 11. It is mainly used for the tendons deployed in a post tensioning system. Tendon bundled with 12 - CFCC 15.2 mm in diameter, can be anchored. However, the processing of this devise attachment has to be carried out under management in a factory. Therefore, it is necessary to check the length of cable with a drawing etc.

![Fig.10 Filling bond method](image)

4.2 Wedge method with buffer material
A typical pictorial presentation of wedge method with buffer material is shown in Fig. 12. The reason for winding buffer material around CFCC is to prevent CFCC from getting crushed and carbon fiber from being cut. This anchoring device can be attached to arbitrary positions on CFCC cable in a precasting factory, at the construction site, or any other place where CFCC is handled. And then this anchoring device can also use CFCC from tendons of a pre-tensioning system in the same way as conventional prestressed concrete steel strand. Presently, it cannot be used as an anchoring system for post-tensioning tendons, because durability test and development of simple tensioning / anchoring systems are not yet completed. It is necessary to develop dedicated tensile fixation system so as to use CFCC as the post-tensioned type tendon for internal and external tendon.

![Fig.12 Wedge method](image)
5. APPLICATION AND ITS RESULTS

Active research was initiated using FRP such as CFCC for reinforcing materials of concrete bridge in Japan since late 1980’s to 1990’s. These research investigations have been summarized as “Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials” [1] by Japan Society of Civil Engineers (JSCE).

5.1 CFCC Applications in Construction
CFCC can be used as any of the followings
- Tendons reinforcing bars and stirrups for the precast beams of pre-stressed concrete bridges
- External cables which are post-tensioned tendons
- Stay cables and other bridge cables
- Tendons for ground anchors

There are numerous applications. Real examples of typical applications to beam are introduced in the following sections.

(1) Shinmiya Bridge (Santoh et al. [5])
Shinmiya Bridge is the first instance where CFCC was used as tendons, and also the first instance in the world of CFRP being used as tendons in a prestressed concrete bridge. Existing reinforced concrete bridge damaged by salt corrosion was planned for the replacement in less than twelve years. In this bridge, CFCC, being high-strength, corrosion-resistant and capable of being handled similarly to conventional prestressing steel, was adopted as a means of combating salt damage in concrete structure.

In addition to that, out of 24 main girders of the bridge, two test girders were erected on either side of the bridge for long-term observation. Loading tests were conducted on the test girders six years after construction, and durability of the bridge was confirmed [6]. This bridge is a pre-tensioned prestressed concrete slab bridge system. Comparison of the former and new Shinmiya Bridge has been passed 20 years after the beginning of using of each bridge, respectively is shown in Fig. 13. No change has been observed in the property of the prestressed concrete bridge after 20 years.

(2) Haranomachi Thermal Power Plant Outfall Bridge
2-span post-tensioned/pre-tensioned concrete simple girder bridge links breakwater to marine facility. These post-tensioned girders were constructed by 3-part precast block method reinforced with CFCC tendons. The outline of this bridge is shown in Fig. 14.

![Fig. 13 Shinmiya Bridge](image1.png)
![Fig. 14 Haranomachi thermal power plant outfall Bridge](image2.png)
(3) Cantilever erection using cable systems (Hisho Bridge: Tsukude C.C.)
The Hisho Bridge was the first application of CFRP in a cantilevered construction, (Hosotani et al. [7]). CFCC were used for all 108 internal (cantilever) and external (span) cables in this post-tensioned structure. Post-tensioning and anchoring methods for 6 strands CFCC multi-cables were developed and applied separately for internal and external cables. Grouting is used for the internal cables, while the CFCC were used unbonded for the external cables. Long-term load monitoring for the bridge is in progress. The side view and cross section of this bridge is shown in Fig. 15.

(4) Cable stayed PC Bridge (Herning Footbridge)
In Denmark a large amount of money is being spent to prevent steel reinforcement corrosion caused by agents that are spread on the road to melt down the snow in winter. Designers wanted to reduce the life cycle cost of prestressed concrete bridge beams by using the CFRP stay cables in large-sized bridge beams. CFCC materials were used for all the stay cables, tendons and also as reinforcement in PC cable stayed bridge. Cross section of this bridge is shown in Fig. 16.

5.2 Research and Development of CFCC in the USA
Ongoing Research has been carried out for the application of CFCC to concrete bridges in the United States since beginning at Lawrence Technological University (LTU), Southfield, Michigan. Initial study was on the application to double-T type beam and in 2002, the Bridge Street Bridge was constructed as the first bridge in the USA for which CFCC was used as the tendon. Cross section and other detail of the Bridge Street Bridge is shown in Fig. 17, (Grace et al. [8]).
Bridge Street Bridge was constructed over the Rouge River in the U.S. (City of Southfield, Michigan) some 20 years ago, and needed rehabilitations because deicing salts caused rust in steel reinforcements. Accordingly, construction of two parallel concrete bridges was planned as a replacement of the failing bridge. Each bridge contains 3 spans over 63 m length and 8.5 m width. One of the bridges was constructed of precast concrete double-T beams that were reinforced, pre-stressed and post-tensioned with rods, tendons and strands produced from CFRP. Funded by Federal Highway Administration (FHWA) and Michigan Department of Transportation (MDOT), the Bridge Street Bridge Deployment Project attracted much attention as United States’s first bridge constructed using CFRP as the principal structural reinforcement. The cutting edge technology that made the project innovative was a brainchild of the research conducted by Prof. Grace-lead team of LTU.

Further studies are being carried out at LTU about the use of FRP products such as CFCC as tendons and non-prestressing reinforcement bars and stirrups to the standard AASHTO beam and box beam. Based on the results of these researches and applications, Michigan DOT is going to use CFCC as the tendon and reinforcing bar for the replacement of beams which have been deteriorated by snow melting agents [9].

6. CONCLUSIONS

(1) CFCC has been developed and commercialized as non-corroding tendons and reinforcing bars that can be used for prestressed concrete structures.

(2) No change has been observed in the property of prestressed concrete bridge after 20 years of usage of CFCC as the structural reinforcing material.

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REFERENCES