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COMPOSITE CABLE POST-TENSIONING SYSTEM**

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INTRODUCTION

The first bridge using a carbon fiber composite cable (CFCC) post-tensioning (PT) system, the Bridge Street Bridge, was built in 2001 in Michigan. Since then, CFCC post-tensioning has been used for four projects in Michigan, one project in Maine, and one project in Louisiana. In regions surrounded by harsh environments, corrosion of steel reinforcement and prestressing strands becomes a major safety, durability, and rehabilitation concern.

Carbon fiber-reinforced polymer (CFRP) materials are one of the alternative solutions because of their corrosion-free nature, durability, high tensile strength, and light weight. Precast prestressed concrete side-by-side box beams have been used in short and midspan bridges. The development of longitudinal cracks in the deck slab between the box beams was one of the major concerns and corrosion-related problems. The longitudinal cracks would allow water and deicing chemicals to penetrate into the sides of the box beams and cause the corrosion of steel reinforcement and concrete spalling. The deterioration of the structures would require the owners costly repairs and rehabilitations followed by replacement of the bridges after 30 to 40 years. To resolve these problems, an unbonded CFCC transverse PT system was designed and developed by the manufacturer. The unbonded CFCC is not susceptible to corrosion due to its corrosion-free nature and allows its force adjustment as well as the replacement of the damaged beams in the future.

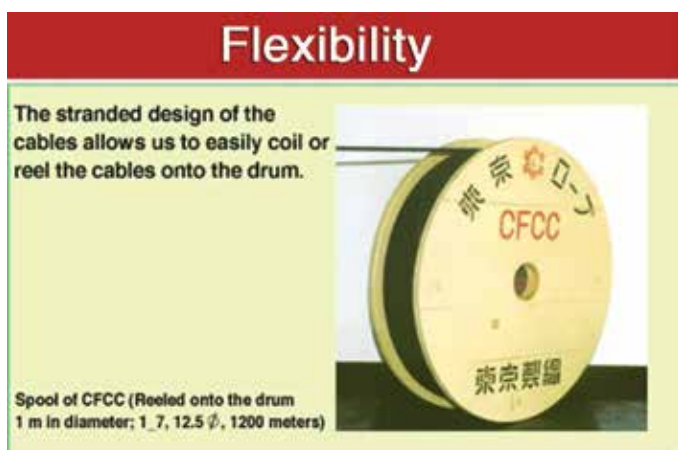


Fig. 1—Features and availability of CFCC.

In Michigan, four side-by-side box beam bridges were constructed using a CFCC transverse post-tensioning system (2011, 2012, 2014, and 2015). In Maine, CFCC strands were transversely post-tensioned for the voided slabs on the Little Pond Bridge in Fryeburg (2012).

CFRP has been used not only for the replacement of the current bridges but also for strengthening existing bridges. In Louisiana, 17.2 mm (0.7 in.) diameter CFCC strands were used as external cables for the I-10 New Orleans East Girder repair (2014).

Because the use of CFRP as post-tensioning and pre-tensioning in highway bridge applications is expected to increase in the future, the drafts of the CFRP design guide-

line for Michigan Department of Transportation (MDOT) and American Association of State Highway and Transportation Officials (AASHTO) have been under development and will be available in the future. The design guideline will allow the highway transportation agencies to consider the use of CFRP among the options in the design of post-tensioning the precast concrete bridge beams and girders as well as the precast concrete decks. The manufacturer's CFCC factory in Michigan, the operation of which started in September 2016, would improve the lead time for delivery and eliminate the transportation cost by an ocean or air shipment.

CHARACTERISTICS OF CFCC MATERIALS

CFCC is a trademarked name of the product, which has been developed by the manufacturer since 1988 (Fig. 1). CFCC is a stranded CFRP and consists of Polyacrylonitrile (PAN)-based continuous carbon fibers with epoxy resins as a binding material.

In addition to its corrosion-free nature, CFCC is characterized by its light weight and high strength. The light weight enhances the workability and handling of the materials.

Guaranteed breaking load of 15.2 mm (0.6 in.) diameter CFCC strand is similar to that of 15.2 mm (0.6 in.) diameter 270 ksi steel strand, Table 1. Relaxation of CFCC is almost the same as low-relaxation steel strand. CFCC has twice the bond strength of steel strand. CFCC does not exhibit any yield phenomenon and its stress-strain relationship is linear to failure. This unique performance influences the design requirements of members with CFCC reinforcement.

POST-TENSIONING ANCHORAGE SYSTEM

The anchorage system is a key for CFCC strands to be used in the field applications. Conventional anchoring

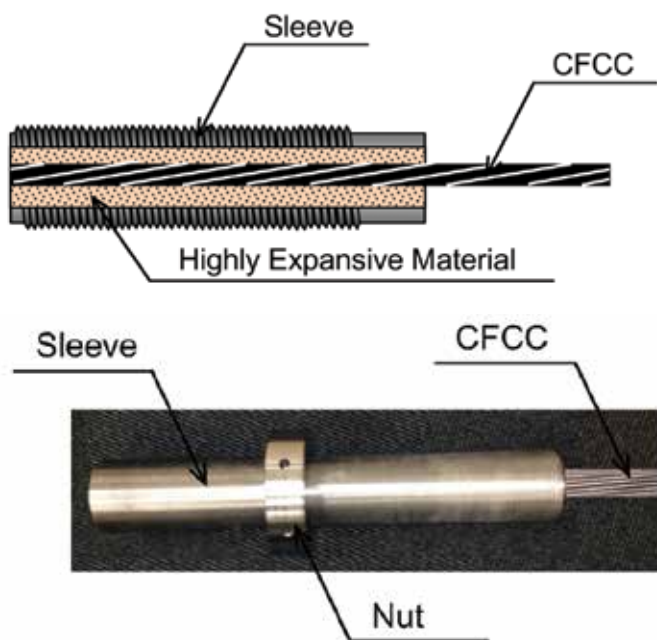


Fig. 2—Post-tensioning 40 mm (1.57 in.) diameter CFCC with pre-installed anchoring devices on both ends.

Table 1: Material Properties

Material	CFCC Strand	Grade 270 Strand
Diameter	15.2 mm (0.6 in.)	15.2 mm (0.6 in.)
Tensile Strength	2,337 MPa (339 ksi)	1,862 MPa (270 ksi)
Cross Sectional Area	115.6 mm ² (0.179 in. ²)	140 mm ² (0.217 in. ²)
Guaranteed Breaking Load	270 kN (60.7 kips)	260.6 kN (58.59 kips)

devices that are used for steel strands are not suitable for CFCC strands in pre-tensioning and post-tensioning as they damage the surface of CFCC strands and cause premature failure at the anchorage.

The anchorage devices for post tensioning are pre-installed on CFCC at the factory. Each CFCC strand is cut to the required length and is anchored at its ends with sockets and nuts using highly expansive grout material. The CFCC strands with pre-installed anchoring devices on both ends are shown in Fig. 2 and then packed and shipped to the field.

The operation of post-tensioning is shown in the following post-tensioning procedure (Fig. 3).

1. Place the bearing plate into the concrete structure.
2. Install the CFCC with a socket into a duct.
3. Place the jack chair and the center hole hydraulic jack, install a nut, and connect a tensioning bar and CFCC with a coupler.
4. Prestress CFCC using a hydraulic pump.
5. Fix the CFCC anchor with a locking nut.
6. Release the center hole hydraulic jack to transfer the prestress to the concrete structure.

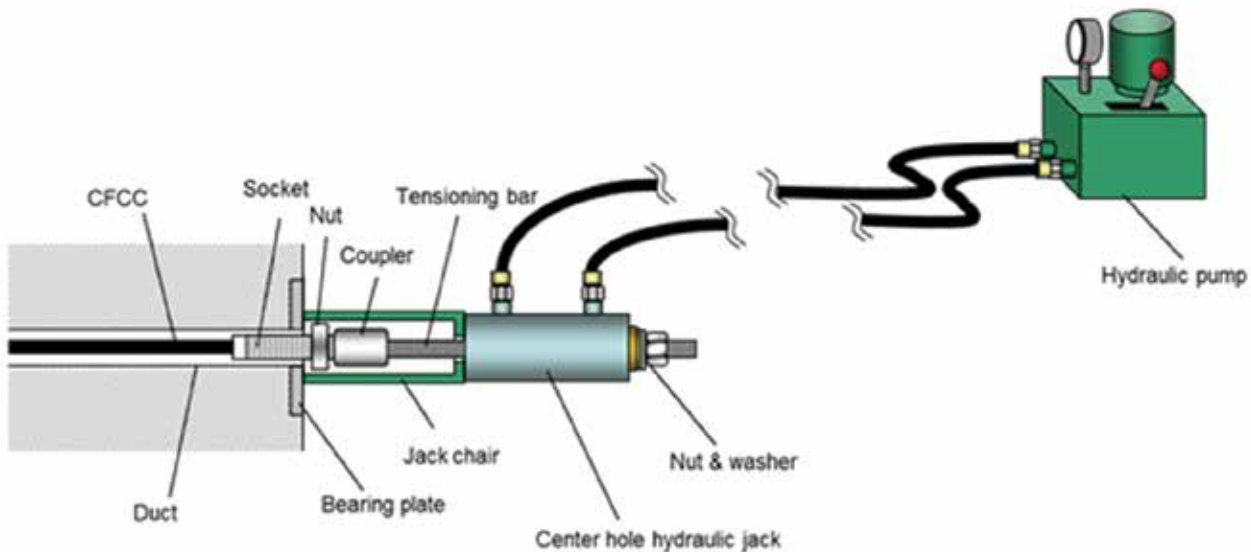


Fig. 3—Post-tensioning procedure.

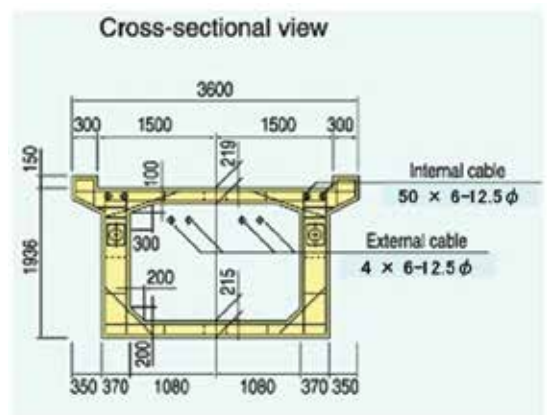


Fig. 4—Hisho bridge side view and cross-sectional view. (Note: All dimensions in mm; 1 in. = 25.4 mm.)

The manufacturer is developing a new system that will not require pre-installed anchoring devices and that will be done in the field. It will consist of mechanical devices with sleeves and wedges, similar to devices for prestressing steel, with different size and shape to avoid premature failure.

ACTUAL DEPLOYMENT OF CFCC POST-TENSIONING IN THE FIELD

(1) Hisho Bridge (1993)

The Hisho Bridge (Fig. 4) is the first application of CFRP in a cantilevered construction. CFCC strands were



Fig. 5—Hanshin Expressway underneath view and installation in a limited area.

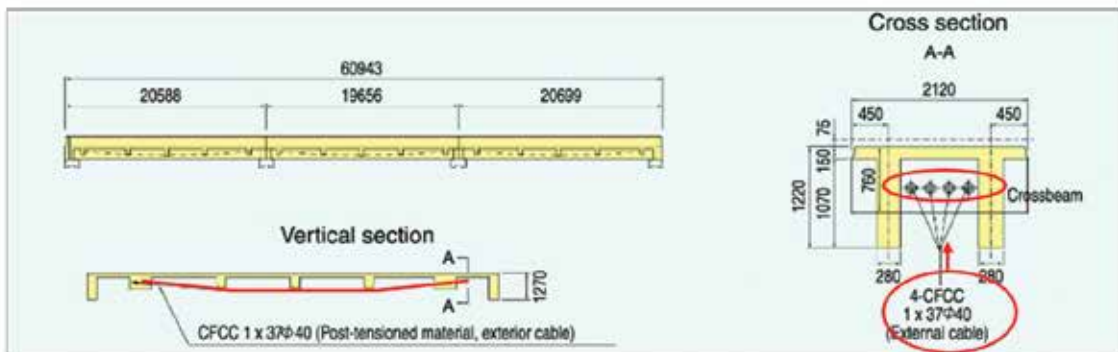


Fig. 6—Bridge Street Bridge cables. (Note: All dimensions in mm; 1 in. = 25.4 mm.)

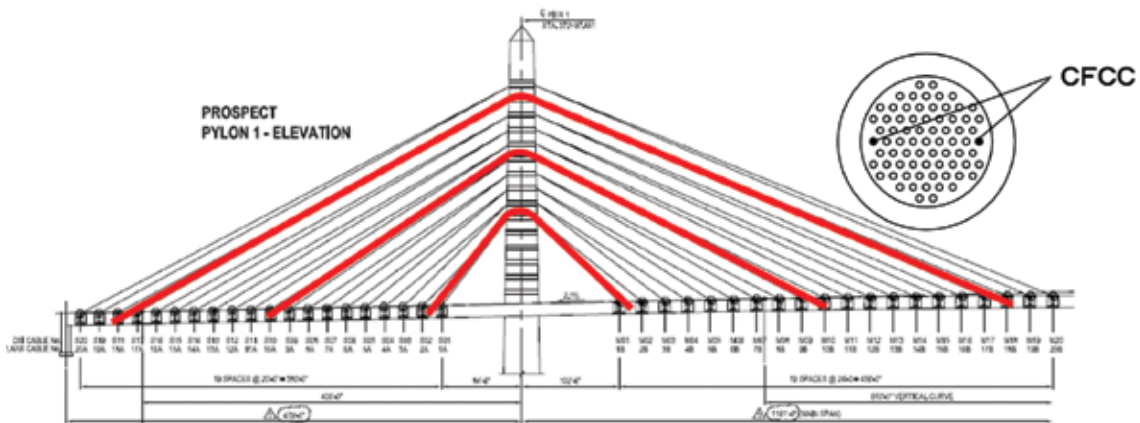
used for internal (cantilever) and external (span) cables in this post-tensioned structure. The number of internal cables is 100 (50 x 2), while the number of external cables is 8 (4 x 2). Post-tensioning and anchoring systems for six-piece multi-type CFCC with 12.5 mm (0.5 in.) diameter were developed and applied, respectively, for internal and external cables. Internal CFCC cables were bonded by grouting the prestressing ducts. External CFCC cables remained unbonded.

(2) Hanshin Expressway, Japan (1999)

An 11-piece multi-type CFCC with 12.5 mm (0.5 in.) diameter was used for external cables of Hanshin Expressway in Japan (Fig. 5). The length of the cables was approximately 20 m (65.62 ft) and installed over five spans to strengthen the existing bridge. The bridge was close to residential areas. Due to its light weight, the workers could pull and install CFCC strands in a limited area without any problems.

(3) Bridge Street Bridge, Southfield, MI (2001)

The Bridge Street Bridge consists of two parallel bridges (Structures A and B) over the Rouge River in the city of Southfield, MI (Fig. 6). Both bridges comprise three spans skewed at 15 degrees over a 62 m (203.41 ft) length. Structure A was constructed of standard AASHTO precast concrete beams, reinforced with conventional steel elements. Structure B was constructed of precast concrete double-tee (DT) beams, reinforced with CFRP. The Bridge Street Bridge was completed and opened for traffic in 2001. Structure B is pre-tensioned and post-tensioned with CFRP strands and tendons. Transverse unbonded CFCC post-tensioning strands with 40 mm (1.57 in.) diameter and 21.8 mm (0.86 in.) diameter were installed through each of seven diaphragms in each span. Load cells were attached to the dead end of each CFCC strand to monitor the force level during the construction and in service. Four externally draped post-tensioning CFCC tendons with 40 mm (1.57 in.) diameter were installed in each DT beam. The draping of these tendons was achieved



Appearance of the bridge



Inside of the bridge

Fig. 7— Penobscot Narrow Bridge.

CASE STUDIES

using a specially designed tendon slide plate and tendon alignment shoe.

Most of the bridges constructed with CFCC in Michigan have been monitored with various sensors by Dr. Nabil Grace's research team at the Lawrence Technological University in Michigan, with a research contract from the Michigan Department of Transportation (MDOT). No signs of degradation, loss of force, or slippage were reported.

(4) Penobscot Narrow Bridge, Maine (2007)

The Penobscot Narrow Bridge, Maine's first cable-stayed bridge, was constructed between May 2003 and December 2006 (Fig. 7). The bridge, with twin pylons and a 2120 ft (646 m) span, uses an innovative cradle system to carry the stays from the bridge deck through a pylon and back to the bridge deck. In each pylon, 20 stays run



Passing CFCC strand through a duct



Post-tensioning of CFCC strand using the same equipment as steel strands



End of post-tensioning strands



Pembroke bridge over Southfield Freeway

Fig. 8—Pembroke Bridge.



Passing CFCC strand through a duct

Fig. 9—M-50/US-127 Highway over Norfolk Southern Railroad.

through individual cradle systems. The unique design features of the cable support and anchorage systems used in this bridge permit the removal, inspection, and replacement of each cable strand while the bridge is in service. It also present engineers with the opportunity to test a variety of cable designs and materials for their longevity and performance in order to better serve the entire bridge industry. The engineers at Maine DOT recognized this, and in June 2007, two epoxy-coated steel strands were removed from each stay at stay numbers 2, 10, and 17 of the north pylon. Two CFCC strands with a diameter of 15.2 mm (0.6 in.) were installed in their places instead. CFCC strands were anchored by the engineers of the manufacturer and installed successfully in the field. A structural monitoring equipment system is installed on CFCC strands to collect data and evaluate their performance for future cable-stayed bridges.

(5) Pembroke Bridge over Southfield Highway, Detroit, MI (2011)

Pembroke Bridge over Southfield Highway M-39 in Detroit, MI (Fig. 8), was the first bridge using a CFCC transverse post-tensioning system in the construction of

the side-by-side box beams. This bridge has two spans with a total length of 32.51 m (106.66 ft). Each span has sixteen 686 mm (27 in.) deep x 1219 mm (48 in.) wide box beams. Box beams were prestressed with 12 low-relaxation steel strands. Each span has six transverse diaphragms at which one 37-wire 40 mm (1.57 in.) diameter CFCC strand was used for transverse post-tensioning to ensure the integrity of the adjacent box beams.

CFCC strand was passed through a 152 mm (6 in.) diameter duct and was tensioned with a force of 685 kN (154 kip) at each diaphragm, which corresponds to 57% of 1200 kN (270 kip) guaranteed breaking load. To monitor the force level during construction and in service, the load cells were attached to the dead end of each CFCC. The bridge opened the service in December 2011. The monitoring system with sensors and load cells started in January 2012, currently in operation and will be continued until September 2020.



Passing CFCC strand through duct

Fig. 10—Little Pond Bridge.



Post-tensioning of CFCC strand



Side view of the bridge with the ends

(6) M-50 Bridge, Jackson, MI (2012)

The M-50/US-127 Highway over Norfolk Southern Railroad (Fig. 9) is the second side-by-side box beam bridge using a CFCC transverse post-tensioning system. This bridge has three spans, and each span is composed of 12 box beams with a depth of 533 mm (21 in.) and a width of 1220 mm (48 in.). The exterior spans have a length of 9.14 m (30 ft) and the interior span has a length of 22.4 m (73.5 ft). There are six transverse post-tensioning cables with a single 40 mm (1.57 in.) CFCC at exterior spans



Passing CFCC strand through a duct



Post-tensioning of CFCC strand



Side view of the Bridge with the ends of CFCC strands

Fig. 11— I-94 Bridges over Lapeer, Port Huron, MI.

and eight transverse post-tensioning cables with a single 40 mm (1.57 in.) CFCC at the interior span. The initial transverse post-tensioning force was 667 kN (150 kip) per diaphragm. This bridge also has a monitoring system and the data will be recorded until 2020.

(7) Little Pond Bridge, Fryeburg, ME (2012)

In the state of Maine, the corrosion of reinforcing steel in concrete has been a constant problem and requires expensive maintenance. This problem was raised due to Maine's coastal environment, harsh winters, and the use of deicing chemicals on the roads and bridges. The Maine DOT decided to use CFCC for the transverse post-tensioning of the precast voided slabs on the Little Pond Bridge, in the town of Fryeburg, ME (Fig. 10). After the bid was made, the project team decided to use five CFCC tendons with a diameter of 40 mm (1.57 in.). In post-tensioning CFCC tendons, the fabricator and contractor can use the same equipment that they normally employ to tension the conventional steel tendons. The polyethylene sheathing was used to protect the CFCC strands.

(8) I-94 Bridges over Lapeer, Port Huron, MI (2014)

Michigan DOT has constructed two side-by-side box beam bridges that carry the east- and west-bound I-94 Highway over Lapeer Road in Port Huron, MI (Fig. 11). This is the first field application in which a CFCC transverse post-tensioning system was used in interstate highway bridges. The east-bound bridge was completed in 2014 and the west-bound bridge was completed 2015. Each bridge has three spans with an exterior span length of 10.67 m (35 ft) and an interior span length of 28.65 m (94 ft), resulting in the total length of 50 m (164 ft). The east-bound bridge is 17.6 m (57.7 ft) wide and is composed of 14 beams. The west bound is 18.8 m (61.7 ft) wide and is composed of 15 beams. The box beams in both bridges have a depth of 840 mm (33 in.) and a width of 1220 mm (48 in.). The east-bound bridge is post-tensioned by 20 CFCC with 40 mm (1.57 in.) diameter with the force of 623 kN (140 kip) per diaphragm. The west-bound bridge is post-tensioned by 20 CFCC with 40 mm diameter with the force of 667 kN (150 kip) per diaphragm.

(9) I-10 New Orleans East Girder Repairs, Louisiana (2014)

Louisiana Department of Transportation and Development (LaDOTD) identified the concrete girders at Interstate 10 west- and east-bound bridges (Fig. 12) as



Post-tensioning cable with load cell

Fig. 12—I-10 New Orleans East Girder Repairs, Louisiana.



Side view of the bridge and post-tensioning cable



Fig. 13— In hot spring areas, due to the strong acid-related environment, steel materials are unusable.

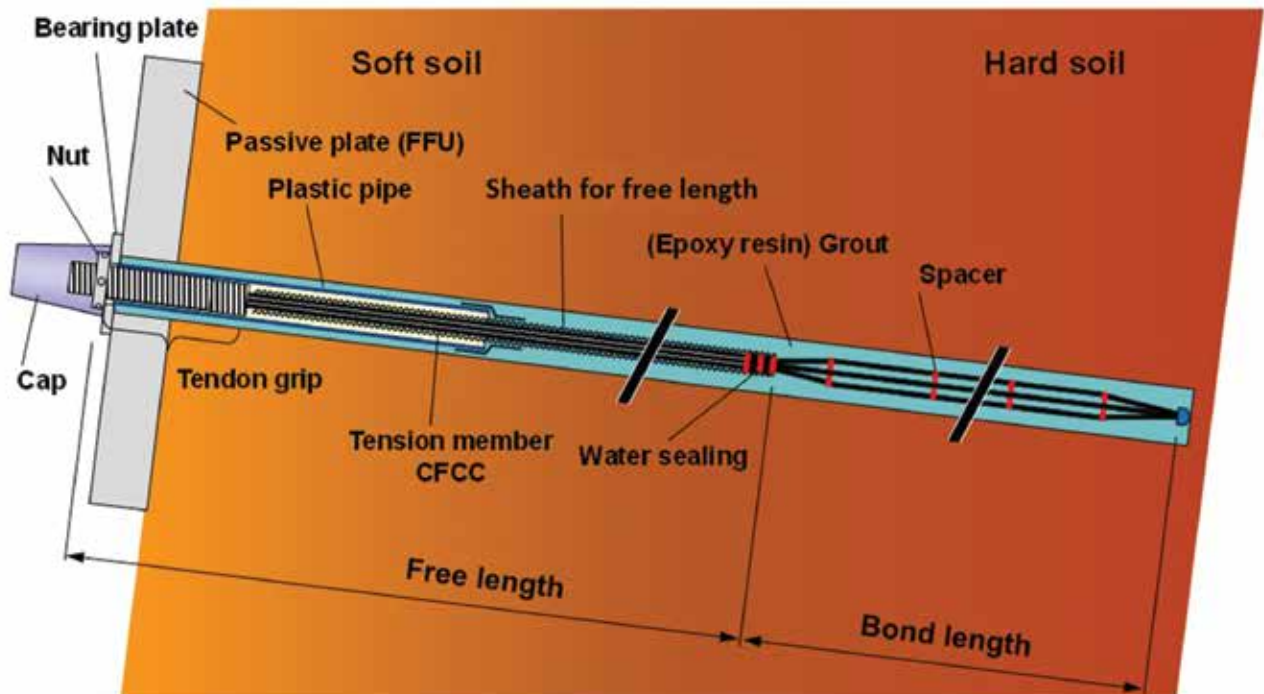


Fig. 14—Ground Anchor System.

being in need of repairs due to the corrosion of steel strands. They selected the two worst bridges, one of which was I-10 Littlewoods, and decided to strengthen the current structures by external cables. One span is east-bound of I-10 Littlewoods, which has six girders that had been strengthened by CFCC with 17.2 mm (0.7 in.) diameter. Each girder has two CFCC external cables. The load cells were installed to monitor the performance of the girders.

(10) Ground Anchor System

Conventional ground anchor systems have been designed and used for slope stabilization and/or landslide prevention, but have been degraded under the highly corrosive environments, such as hot spring areas in Japan (Fig. 13).

The Ground Anchor System using the following new materials has been developed in 1993 (Fig. 14).

1. Carbon-fiber composite cable tendons
2. Fiber-reinforced foamed urethane (FFU) passive plates
3. (Epoxy resin) grout

To demonstrate the life of the newly developed ground anchor system, a 5-year long-term exposure test had been performed from 2001 to 2006 (Fig. 15). Five years monitoring in the field had been done at a hot spring area with pH value in the 3 to 4 range and temperatures ranging from 60 to 100°C (140 to 212°F). Conventional steel strands and cement grout were deteriorated severely. However, CFCC strands showed neither degradation in strength nor visible defects. Fiber-reinforced foamed urethane passive



Exposure test and deterioration of sampled specimens at year 3

Fig. 15—Exposure test of newly developed ground anchor system using CFCC.



Steel strand: Crumbled by rust



Easy handling at the narrow space

Fig. 16—Installation of new ground anchor system using CFCC.



No water pollution



Test setup



CFCC strands with pre-installed anchoring devices

Fig. 17—Research test configuration.

plates maintained stable properties. The resin grout kept its required compressive strength for design.

The new ground anchor system has been used in Japan with the installation of over 80 projects (Fig. 16). The benefits of the new Ground Anchor System are as follows:

1. No need for double protection due to the corrosion-free characteristic of CFCC.
2. No maintenance required for CFCC ground anchor system.
3. Eco-friendly and no water pollution as no grease is used.
4. Workability in a limited area due to its light weight.
5. No need for heavy equipment such as a large-scale crane.

As previously stated, the new ground anchor system can be used for slope stabilization and/or landslide prevention in strong acid-related environments. It can be also used to strengthen the structures for seawalls in coast area, ports/harbors, and dams.

RESEARCH PROJECT

The University of Nevada, Reno, has done the research project, the title of which is “Precast Square Column with UHPC in Plastic Hinge Zone and CFRP Tendons with Pocket Connection to Footing.” Two CFCC tendons with diameters of 34 mm (1.34 in.) were used to investigate the effectiveness of CFRP tendons in minimizing residual displacement (re-centering the column) under strong earthquakes (Fig. 17). The initial post-tensioning force was 289 kN (65 kips) per tendon corresponding to 24% of the guaranteed capacity. The maximum tensile stress of the tendons reached 64% of the guaranteed capacity of 1200 kN (270 kips) during the test. The CFCC tendons performed well as intended and eliminated the residual drift during different levels of earthquake

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