The Taylor Bridge, the world’s longest span bridge using carbon fiber reinforced polymer (CFRP) as prestressing and shear reinforcement for the bridge girders, was recently completed in Headingley, Manitoba, Canada. CFRP was also used to reinforce part of the deck slab, while glass fiber reinforced polymer (GFRP) reinforcements were used in part of the barrier wall.

Known as a “smart” structure because of the new generation of fiber optic sensing technology used to monitor its performance on a daily basis, the bridge is instrumented with fiber optic sensors coupled with conventional electric strain gages embedded in the bridge girders, deck slab, and barrier wall. Data are transmitted through two telephone lines for continuous monitoring of the performance of the bridge under traffic loads and extreme environmental conditions. The bridge is also monitored with a camera to provide video information synchronized with the fiber optic sensor readings.

The bridge was opened to traffic in October 1997 and involved cooperation from the following organizations: ISIS Canada, Network of Centres of Excellence; Manitoba Highways and Transportation; Wardrop Engineering, Inc., Winnipeg, Manitoba; Con-Force Structures, Ltd., Winnipeg, Manitoba; Mitsubishi Chemical Corp., Japan; Tokyo Rope Mfg. Co., Ltd., Japan; Marshall Industries Composites, Inc., Ohio, USA; and ElectroPhotonics Corp., Toronto, Canada.

### Bridge description

The Taylor Bridge is located on Provincial Road No. 334 over the Assiniboine River in the Parish of Headingley, Manitoba. The total length of the bridge is 165 m (542 ft); it is divided into five equal spans, with each span consisting of eight 1.8 m (6 ft) deep I-shaped precast prestressed concrete girders. The cross sections of the bridge girders are shown in Fig. 1.

### Materials

Two different types of CFRP reinforcement were used. Carbon fiber composite cables (CFCC) of 15.2 mm (0.60 in.) diameter, produced by Tokyo Rope in Japan, were used to pretension two girders, while the other two girders were pretensioned using 10 mm (0.40 in.) diameter indented...
Leadline bars, produced by Mitsubishi Chemical Corp. in Japan. Two of the four girders were reinforced for shear using 15.2 mm (0.60 in.) diameter CFCC stirrups and 10 x 5 mm (0.4 x 0.2 in.) Leadline stirrups with a rectangular cross section. The other two beams were reinforced for shear using 15.2 mm diameter epoxy-coated steel stirrups.

The deck slab was reinforced by 10 mm diameter indented Leadline bars similar to the reinforcement used for prestressing. C-BAR (GFRP) reinforcement of 15 mm diameter, produced by Marshall Industries Composites, Inc., USA, was used to reinforce a portion of the Jersey-type barrier wall. Double-headed stainless steel tension bars of 19 mm (0.75 in.) diameter were used for the connection between the barrier wall and the deck slab.

Reinforcement details

Among the notable features of the Taylor Bridge are the use of FRP as shear reinforcement and the first-time use of draped prestressing tendons in a field application. A typical steel girder was prestressed by 26 straight and 14 draped steel strands. Thirty-two straight and 14 draped cables were used for girders prestressed by CFCC, while 38 straight and 18 draped bars were used for the other girders prestressed by Leadline, as shown in Fig. 1.

The girders were reinforced for shear using double leg stirrups spaced at 400, 300, and 100 mm (16, 12 and 4 in.) for steel, CFCC, and Leadline stirrups, respectively. The stirrups were projected out of the top surface of the girder, as shown in Fig. 1, to act as shear connectors and to provide the composite action between the girder and the deck slab. A 16 x 8 m (53 x 26 ft) portion of the 275 mm (11 in.) depth deck slab was reinforced by 10 mm indented CFRP Leadline bars. The bottom reinforcement consisted of two 10 mm bars spaced at 125 mm (4.92 in.) in the main direction and 10 mm bars spaced at 125 mm in the direction of the bridge girders. The top reinforcement consisted of 10 mm bars spaced at 125 mm in each direction. A 14.2 m (46.6 ft.) long Jersey-type barrier wall was reinforced by two layers of 15 mm C-BAR. Double-headed stainless steel bars spaced every 300 mm were used to anchor the barrier wall to the bridge deck slab.

Monitoring system

A total of 63 single and two multiplexed fiber optic sensors were installed on the CFRP, GFRP, and steel reinforcement to monitor the bridge from a central monitoring station located remotely away from the bridge. The 65 sensors were installed on the following bridge component reinforcements, as shown in Fig. 2:

- Girders reinforced by CFRP.
- Selected girders reinforced by steel.
- Deck slab portion reinforced by CFRP.
- Barrier wall portion reinforced by GFRP.

In addition, 20 thermocouples were used at different locations of the bridge to compensate for the temperature change. A 32-channel fiber optic grating strain indicator (FLS 3500R), was used for strain measurements. The system is connected to a computer to download the strain readings using a telephone line. (A general description for the Taylor Bridge monitoring system is given in Fig. 2.)

The bridge is also being monitored by 26 conventional electrical strain gages mounted on the reinforcement to verify the readings of the optic sensors. A 32-channel data logging system (CR 10X) and two 16-channel multiplexing units are used for strain measurements. This system is also connected to an internal modem to download the strain data using an additional telephone line. Both the fiber optic multiplexing units and the data logging system were installed in a heated enclosure located in the cross diaphragm under the bridge deck slab.

Research

Due to a lack of design codes, several research projects were conducted at the University of Manitoba to examine the performance of the bridge. The research projects included testing of a scale model of the bridge girders and a full-scale model of the deck slab. Straight and draped CFRP reinforcements were also tested under axial tension. CFRP performance as shear reinforcement, including the effect of the bent of stirrups and the orientation of inclined cracks on tensile strength, was investigated.

Transfer and development lengths of the CFRP reinforcement were also evaluated and a theoretical model was introduced. In addition, a research project was conducted at the Ministry of Transportation of Ontario to examine the barrier wall and the deck slab for steel-free bridge decks.

Structural design

Bridge girders prestressed and reinforced by CFRP were designed to ex-
The prestressing force and the eccentricity of the reinforcement were the same for all girders. The prestressing level was 60 and 63 percent of the guaranteed ultimate tensile strength for CFCC cables and Leadline bars, respectively, compared to 75 percent for steel strands.

The flexural design of the girders prestressed by CFRP reinforcement was based on equilibrium, strain compatibility, and the material characteristics of CFCC, Leadline, and concrete. The predicted flexural behavior of girders prestressed by CFRP was identical to that of girders with steel before cracking, as shown in Fig. 3. The design capacity of girders with CFRP based on the ultimate strength of the reinforcement was 50 percent higher than that of the girder with steel. It should be noted that the ultimate tensile strength of CFRP reinforcement is higher than the guaranteed value reported by the manufacturer. Based on AASHTO Code 1989, the girders reinforced by CFRP were designed for a stress level in the stirrups of 250 MPa (36 ksi) at factored applied load, compared to 200 MPa (29 ksi) stress level used for the steel stirrups. This stress in the CFRP stirrups is lower than 30 percent of its ultimate capacity.

**Failure mechanism**

The concept of providing an alternative load path has been used in the design of the bridge to avoid progressive collapse in case of failure of one of its components. The cross diaphragms were designed to support the dead load of the bridge in case of the unlikely event of failure of the two girders prestressed by CFRP. In addition, non-prestressed reinforcements were provided in the girders prestressed by CFRP to develop catenary action in case of breakage of all of the stressed reinforcement.

**Construction details**

CFRP reinforcement was delivered in rolls of 2.5 and 1.75 m (8.2 and 5.7 ft.) diameter for Leadline and CFCC, respectively. The Leadline bars were cut on site, while the CFCC cables were delivered precut to the specified length with 300 mm (11.8 in.) die cast at each end of the cable. Prestressing of CFRP was adapted to the precast industry by coupling the CFRP reinforcement to 12.7 mm (0.50 in.) diameter steel strands to facilitate prestressing using the same jacking process used for the steel strands.

The prestressing reinforcement was draped at two points, 7.15 m (23.5 ft) apart, using a specially detailed hold-down system. The system consisted of 14 and 18 steel rollers for girders prestressed by CFCC and Leadline, respectively. Two push-up systems were used beyond the two ends of the girders to retain the straightness of the draped reinforcement. Due to the large movement of the draped CFRP reinforcement during jacking at one end of the beam, a special push-up system was used. The system was made of high-density polyethylene plate of 25.4 mm (1 in.) thickness. Details of the girder reinforcement prestressed by CFCC are shown in Fig. 4.

The strain in the CFRP reinforcement was monitored during transportation and the measured values were very small. The top and bottom CFRP reinforcements of the deck were assembled on-site and placed on top of the precast girders. The CFRP and steel reinforcement of the cast-in-place deck slab are shown in Fig. 5. Detailing of the GFRP reinforced barrier wall and the connection between the barrier wall and the deck slab are also shown in Fig. 5. The fiber optic sensors and electric strain gages were installed on the reinforcement at the precast plant for the bridge girders and on-site for the deck slab and the barrier walls.

**References**

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