FRP FOR LARGE SPAN HIGHWAY BRIDGE IN CANADA

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SUMMARY

The Province of Manitoba in Canada accepted the challenge to use carbon fibre reinforced polymer (CFRP) reinforcements for prestressing and as stirrups for 32.5 metre I-girders and a portion of the concrete deck slab of a concrete highway bridge in Headingley, Manitoba, Canada. Part of the barrier wall will also be reinforced by glass fibre reinforced polymer (GFRP) reinforcements. The bridge is instrumented with fibre optic sensors and electric strain gauges connected to a telephone line for continuous monitoring of the performance of the bridge. This paper reviews the research work undertaken at the University of Manitoba prior to the construction of the bridge, design philosophy, construction details, and monitoring system.

1. INTRODUCTION

Construction of the world’s largest span bridge using CFRP as prestressing and shear reinforcement for four girders is currently underway in Headingley, Manitoba, Canada. CFRP is also used to reinforce a part of the deck slab, while GFRP reinforcements are used in a part of the barrier wall. The bridge is instrumented with fibre optic sensors coupled with conventional electric strain gauges embedded in the bridge girders, deck slab, and barrier wall. Data will be transmitted through a telephone line for continuous monitoring of the performance of the bridge under traffic loads and extreme environmental conditions. The bridge will also be monitored with a camera to provide video information synchronized with the optic sensors readings. The scheduled completion date for the bridge is October 1997.

Due to a lack of design codes, several research projects were conducted at the University of Manitoba to examine the performance of the bridge. Models of the bridge girders and the deck slab were tested. Straight and draped CFRP reinforcements were also tested under axial tension. Performance of CFRP as shear reinforcement including effect of bent of stirrups and orientation of the crack on the tensile strength was examined. Transfer and development lengths of the CFRP reinforcement were also evaluated and a theoretical model was introduced.

2. BRIDGE DESCRIPTION

The 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 165.1 metres,
divided into five equal spans. Each span consists of eight I-shaped precast prestressed concrete girders as shown in Fig. 1.

![Diagram of bridge layout](image)

*Fig. 1 Layout of the bridge*

### 2.1 Materials

Two different types of CFRP reinforcements were used. Carbon fibre composite cables (CFCC) of 15.2 mm diameter, produced by Tokyo Rope, Japan, were used to pretension two girders while the other two girders were pretensioned using 10 mm diameter indented Leadline bars, produced by Mitsubishi Chemical Corporation, Japan. Two of the four girders were reinforced for shear using 15.2 mm diameter CFCC stirrups and 10 x 5 mm Leadline bars of rectangular cross section. The other two beams were reinforced for shear using 15 mm diameter epoxy coated steel rebars.

The deck slab was reinforced by 10 mm diameter indented Leadline bars similar to the reinforcement used for prestressing. C-BAR (GFRP) reinforcement of 12.5 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 diameter were used for the connection between the barrier wall and the deck slab. Material properties of FRP reinforcement used in the bridge are shown in Table 1.

<table>
<thead>
<tr>
<th>type of reinforcement</th>
<th>shape</th>
<th>dimensions mm</th>
<th>area mm²</th>
<th>guaranteed strength MPa</th>
<th>elastic modulus GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFCC</td>
<td>7 wire</td>
<td>15.2</td>
<td>113</td>
<td>1750</td>
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<tr>
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<td>10</td>
<td>71.8</td>
<td>2250</td>
<td>147</td>
</tr>
<tr>
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<td>10 x 5</td>
<td>38.5</td>
<td>1800</td>
<td>140</td>
</tr>
<tr>
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<td>circular</td>
<td>12.5</td>
<td>113</td>
<td>713</td>
<td>42</td>
</tr>
</tbody>
</table>

*Table 1: Material properties of FRP reinforcement*
The anchorage system used for CFCC was the die cast wedge type, where a 300 mm steel tube is attached to the cable by a low point braze alloy. Steel wedges were used to clamp individual cables to an anchorage head, similar to the conventional method for prestressing cables. The 10 mm Leadline bars were anchored using 150 mm long steel wedges and a steel anchor head. Aluminum tubes were placed between the Leadline bars and the steel anchorage to reduce the transverse stresses in the bars. Both anchorage systems were supplied by the manufacturers of the reinforcement.

A typical bridge girder was pretensioned using 12.7 mm steel strands with a cross sectional area of 99.0 mm². The ultimate tensile strength and modulus of the steel were 1860 MPa, and 190 GPa, respectively. Epoxy coated 15 mm steel rebars with a yield stress of 400 MPa were used as stirrups for the other girders. The specified concrete strength for the bridge girders was 30 MPa at release and 40 MPa after 28 days. The specified concrete strength of the deck slab and the barrier wall is 30 MPa.

2.2 Reinforcement Details

A typical steel girder was prestressed by 26 straight and 14 draped steel strands. 32 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.2. The girders were reinforced for shear using double leg stirrups at 400, 300, and 100 mm for steel, CFCC and Leadline stirrups respectively. The stirrups were projected out of the top surface of the girder to act as shear connectors and to provide the composite action between the girder and the deck slab.

Two layers of the CFCC and Leadline reinforcement were debonded at the ends of the girder using PVC pipes in order to avoid high tensile stresses at the end zone of the girders. CFRP circular stirrups of 120 mm diameter with a spacing of 100 and 150 mm for CFCC and Leadline girders, respectively, were used at the end zone, as shown in Fig. 2, in order to provide confinement of the concrete and to avoid any possible splitting cracks at this region. Details of the reinforcement of the girder prestressed by CFCC are shown in Fig.3.
A 16 x 8 m portion of the 275 mm depth deck slab was reinforced by 10 mm indented Leadline bars. The bottom reinforcements were 2-10 mm bars spaced at 125 mm in the main direction and 1-10 mm bar spaced at 125 mm in the direction of the bridge girders. The top reinforcement consisted of 1-10 mm bar spaced at 125 mm in each direction. A 14.2 metre-long Jersey type barrier wall was reinforced by two layers of 12.5 mm C-BAR spaced at 100 mm in each direction. Double headed stainless steel bars spaced every 300 mm were used to anchor the barrier wall to the bridge deck slab, as shown in Fig. 4.

2.3 Monitoring System

A total of 64 fibre optic sensors were installed on the CFRP, GFRP and steel reinforcement to monitor the bridge from a central monitoring station remote from the bridge. The sensors included single Bragg and 3-fibre Bragg grating sensors to measure the local strain and the strain profile along the reinforcements. In addition, 17 thermocouples were used at different location of the bridge to compensate for the temperature change. A 32-channel Bragg grating fibre laser sensor system is used for strain measurements. The system is connected to a modem to download the strain readings using a telephone line. The bridge will also be monitored by 26 conventional electrical strain gauges mounted on the reinforcement used to verify the readings of the optic sensors.

Fig. 3 Details of reinforcement of beam prestressed by CFCC

Fig. 4 Reinforcement details of the barrier wall
3. RESEARCH PROJECTS

Several research projects were conducted at the University of Manitoba to examine the behaviour of the different components of the bridge. The research projects included a scale model of the bridge girders and a full-scale model of the deck slab [1,2]. Design aspects such as capacity of CFRP as shear reinforcement, bond characteristics of CFRP, and capacity of draped reinforcement were also investigated [3,4]. In addition, a research project was conducted at the Ministry of Transportation of Ontario (MTO) to examine the connection between the barrier wall and the deck slab for steel-free bridge decks [5].

3.1 Bridge Girders Model

Six concrete beams prestressed and reinforced for shear by the same type of reinforcement used for Headingley bridge were tested up to failure. The beams were 1:3.6 scale models of the bridge girders and have a span of 8.9 metre as shown in Fig. 5. The flexural behaviour of beams prestressed by CFRP reinforcement showed similar stiffness to the beam prestressed by steel strands after cracking up to yielding of the steel. The capacity of the beams prestressed by CFRP reinforcement was 20 to 45 percent higher than that for the beam prestressed by steel [1].

![Fig. 5 Test set-up of the bridge girders model](image1)

3.2 Deck Slab Model

A full-scale model of a portion of the deck slab was tested using an equivalent truck wheel load [2]. The model consisted of three continuous spans, 1.8 metre each, and two cantilevers with overall dimensions of 7.2 x 3.0 metres and thickness of 200 mm as shown in Fig.6. Each span and the two cantilevers were tested independently using a quasi-static concentrated load. Optical fibre sensors were used to monitor the strain of the reinforcement in conjunction with conventional electrical strain gauges. The failure load of the slab had a lower bound of 1000 kN which is more than 10 times the service load according to the AASHTO specifications.

![Fig. 6 Test set-up of the bridge deck model](image2)
3.3 CFRP for Shear Reinforcement

The behaviour of the CFRP stirrups was investigated by testing six beams reinforced by different types of stirrups as shown in Fig. 7. Effect of bent at the stirrup anchorage and kinking that occurs when the stirrup intersects the shear crack were studied. A stress level of 50 percent of the guaranteed strength of the straight reinforcement could be considered as a limit of the strength of the CFRP stirrups [3].

3.4 Bond Characteristics of CFRP Prestressing Reinforcement

Transfer and development lengths of CFRP prestressing reinforcement were investigated. A total of 52 prestressed concrete beams and prisms were tested [4]. Effect of type of reinforcement, diameter of reinforcement, jacking stress, concrete strength, confinement of concrete, creep and shrinkage of concrete on the bond characteristics were examined. Based on the experimental results, two models were proposed to determine the transfer and development lengths of CFRP reinforcement.

4. STRUCTURAL DESIGN

Bridge girders prestressed and reinforced by CFRP were designed to have the same behaviour as that of girders prestressed with steel strands under service loading conditions. The prestressing force and the eccentricity of the reinforcement were kept 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. Table 2 summarizes the prestressing forces at jacking, transfer and final stages.

<table>
<thead>
<tr>
<th>type of reinforcement</th>
<th>no. of reinforcement</th>
<th>prestressing force (kN)</th>
<th>jacking stress to guaranteed strength</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>jacking</td>
<td>transfer*</td>
</tr>
<tr>
<td>steel</td>
<td>40-D12.7</td>
<td>5508</td>
<td>5052</td>
</tr>
<tr>
<td>Leadline</td>
<td>56-D10</td>
<td>5670</td>
<td>5255</td>
</tr>
<tr>
<td>CFCC</td>
<td>46-D15.2</td>
<td>5524</td>
<td>5060</td>
</tr>
</tbody>
</table>

* immediately after release  ** after 40 days

Table 2 Prestressing forces for the different bridge girders

Flexural design of girders prestressed by CFRP reinforcement was based on strain compatibility and the material characteristics of CFCC, Leadline, and concrete. The predicted flexural behaviour of girders prestressed by CFRP was identical to that of girders with steel before cracking as shown in Fig. 8. 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 as shown in Fig. 8. It should be noted that the ultimate tensile strength of CFRP reinforcement is higher than the guaranteed value reported by the manufacturer [6].

The girders reinforced by CFRP were designed to have a stress in the stirrups of 250 MPa at factored applied load based on AASHTO code 1989, compared to 200 MPa in the steel stirrups. This stress in the CFRP stirrups represents less than 30 percent of its capacity.

**Fig 8 Flexural capacity of bridge girders**

4.1 Failure Mechanism

The concept of providing an alternative load path has been applied to the bridge in order 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 reinforcement were provided in the girders prestressed by CFRP to develop catenary action in the member in case of breakage of all the stressed reinforcement [7].

5 CONSTRUCTION DETAILS

CFRP reinforcement was delivered in rolls of 2.5 and 1.75 m diameter for Leadline and CFCC respectively. The Leadline bars were cut at the site, while CFCC cables were delivered precut to the specified length with 300 mm 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 diameter steel strands, as shown in Fig.9, to facilitate prestressing using the same jacking process used for the steel strands [8].

**Fig 9 Couplers for prestressing**  **Fig.10 Hold down system**
The prestressing reinforcement was draped at two points, 7 m apart, using a hold down system as shown in Fig. 10. The system consisted of 14 and 18 steel rollers for girders prestressed by CFCC and Leadline respectively. The rollers were 32 mm diameter supported by steel bearing to facilitate moving of the rollers and reduce the friction between the reinforcement and the rollers. Two push up systems were used beyond the two ends of the girders to retain the draped reinforcement straight. 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, as shown in Fig. 11. The system was made of high density polyethylene plate of 27 mm thickness.

The girders were transported to the site and installed on the piers. The strain in the CFRP reinforcement was monitored during transportation and no change in the strain was observed. Construction and handling of the bridge girders are shown in Fig. 12.

Fig. 11 Push up system  Fig. 12 Construction of the bridge

REFERENCES

3. MORPHY R., SHEHATA E., and RIZKALLA S., Bent Effect on Strength of CFRP Stirrups, Accepted for Publication in the Proceedings of FRPRCS-3, to be held in October 1997, Sapporo, Japan.