FRP FLEXURAL AND SHEAR REINFORCEMENTS FOR HIGHWAY BRIDGES IN MANITOBA, CANADA

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Abstract
The province of Manitoba accepted the Challenge to construct the world largest span concrete highway bridge prestressed and reinforced for shear using carbon fibre reinforced plastic (CFRP) reinforcement. Portion of the concrete deck slab is also reinforced exclusively by FRP reinforcements. This paper describes the experimental program conducted at the University of Manitoba, Canada to examine the behaviour of 1:3.6 scaled model of the bridge girders. The paper discusses the construction details of the test beams which are identical to those planned for the bridge girders. Preliminary test results including flexural behaviour, shear behaviour and modes of failure are presented.
Keywords: Beam, bridge, carbon, FRP, model, shear, prestressed concrete.

1 Introduction
Bridges in Canada are exposed to harsh environments characterized by a wide range of temperature variation and use of salt for de-icing in addition to the typical effects of cyclic and impact loads of traffic. The cost of correcting corrosion-induced distress in bridges is high compared to the capital cost of the structure. To overcome this problem the province of Manitoba is undertaking the challenge to construct the largest span highway concrete bridge with 32.5 meter span using two types of CFRP reinforcements for prestressing and stirrups. The two types of CFRP are Carbon fibre Composite Cable, CFCC, produced by Tokyo Rope, Japan and Leadline produced by Mitsubishi Kasei, Japan. In addition to their corrosion-resistant characteristics, the two types of materials have outstanding characteristics in terms of high strength-to-
weight ratio, high fatigue strength, low relaxation, non-magnetic conductivity, and ease of handling and installation due to their light weight.

The paper describes the experimental program undertaken at the University of Manitoba to test a total of six beams 1:3.6 scaled of the bridge girders. The beams have an I-shape cross section, with the same span to depth ratio and prestressed level of the bridge girders. All beams are 9.3 meters long and 500 mm in depth. A 50 mm top slab was casted, after a minimum age of 7 days of the pretensioned beam to provide the composite action similar to the actual bridge deck slab.

The main features of this test program are the use of CFRP for shear reinforcements, draping of the prestressing strands, and extending the CFRP stirrups into the slab to provide the dowel action similar to the deck slab of the bridge.

2 Bridge outline

The bridge consists of five spans, 32.5 meters each, covering a total length of 165.1 meters. The bridge is located over the Assiniboine River, Parish of Headingley, Winnipeg, Manitoba, Canada. All the bridge girders are precast pretensioned and simply supported. The bridge girders have an I-section AASHTO type, transversely spaced at 1.8 meter and supporting 187 mm thickness deck slab. A typical pretensioned concrete girder is shown in Fig.1.

![Fig.1 Pretensioned concrete bridge girder](image)

3 Experimental program

The main objective of the experimental program is to evaluate the performance of prestressed concrete I-girders totally reinforced by FRP reinforcements for shear and prestressing in terms of flexural cracks, deflection, and ultimate resistance. The study is focused on the effect of different stirrups sizes on the shear resistance in terms of the diagonal crack width, crack distribution and the dowel action. The beams were also tested to examine the efficiency of the draped prestressing CFRP tendons with
an angle of four degrees, which is typically used for the bridge, to achieve uniform and allowable stresses distribution at the ends of the girders.

The test beams were 1:3.6 scale model to the bridge girders. The test beams were designed to have the same span to depth ratio of 17.8 and the same induced stresses in the section due to prestressing as the bridge girders. Due to lack of information in the literature on the performance of FRP as shear reinforcement, various stirrup sizes were used to study their effect on the shear and flexural behaviour.

A total of six beams, 9.3 meters long, were fabricated for this experimental program. All the test beams had an I-shape cross section of an overall depth of 500 mm as shown in Fig.2. The top slab was 500 mm wide and 50 mm depth. Similar to the prototype girders, 40% of the prestressing reinforcement were draped at a distance of 40% of the span from the beam ends with 40° angle. The hold down system used for the test beams consisted of steel pins of 33 mm diameter and a sleeve free to rotate as shown in Fig.3. All the stirrups were exposed from the girders into the slabs to provide the dowel action needed to simulate the composite behaviour.

Fig.2 Detailing of test beam prestressed by CFCC

Fig.3 Details of the hold down system

Three of the beams were prestressed by five 15.2 mm CFCC seven wires cables each and reinforced by three different sizes of two branches CFCC stirrups. The three sizes were 7.5 mm seven wires cables, 5 mm seven wires cables and 5 mm solid
cables. Two beams were prestressed by ten 8 mm Leadline rods and reinforced by two different configurations of Leadline stirrups, single and double legged stirrups. The Leadline stirrups had a rounded corner rectangular cross section of an equivalent area of 7 mm diameter rods. The sixth beam was prestressed by five 13 mm conventional steel seven wires strands and reinforced by steel double legged stirrups as a control specimen. The stirrups of the six beams were spaced uniformly within the I-shape portion of the beams 110 mm apart. Typical configuration of the CFRP single and double legged stirrups is shown in Fig.4.

Since the scale factor is not applicable to the unit weight of the concrete, the resulting stresses at the top surface of the girder, due to the effect of prestressing and the self weight, exceeded the allowable tensile stresses. Therefore, temporarily external post-tensioning was used to provide additional stresses on the cross section as shown in Fig.2. The induced stresses in the beams were equivalent to that of the prototype.

![Fig.4 Details of the CFRP stirrups](image)

3.1 Construction details
Test beams were fabricated by Con-force structures company Ltd, Winnipeg, Manitoba, Canada. Steel couplers were used to couple the CFCC and Leadline prestressing reinforcement to conventional steel strands to minimize the cost of CFRP and facilitate using the same jacking system of the precast fabricators. In order to prestress the draped reinforcement, a special setup was used as shown in Fig.5. The hold-down system was supported by the steel side of the form which was braced to the floor. Fig.5 also shows the hold-up system used to provide the change in the direction of the draped reinforcement to the horizontal position for jacking purposes.

Typical fabrication of the test beams started by jacking the bottom straight strands followed by assembling the stirrups. The steel sides of the form were assembled to support the hold-down pins required for the draped reinforcement. After the concrete had reached its specified strength, the beams were supported downwards by vertical posts at the pins locations to remove the two sides of the form supporting the hold down pins. The draped prestressed reinforcement was released and the vertical posts holding down the beam were removed. External post-tensioning was applied to control the camber using two steel strands located beneath the top flange and
anchored to the end blocks as shown in Fig.2, followed by releasing the bottom straight prestressed tendons. Top slab was casted after a minimum age of 7 day from releasing the prestressed tendons.

![Diagram of prestressing system](image)

**Fig.5** Details of the prestressing system

### 3.2 Test setup

The testing program was conducted at the Structural Engineering and Construction R&D Facility, University of Manitoba using the setup shown in Fig.6. Spreader beams were used to apply four concentrated loads to simulate an equivalent truck loading condition. Lateral supports were provided at four locations along the span. A ± 1.2 million pounds MTS testing machine was used to apply the load using deflection control mode. Deflection at mid-span was measured from both sides using Linear Motion Transducers (LMT). Dial gauges were used to monitor any possible slip of the tendons or relative slip between the girder and the top slab. Demec point stations of the "Rosette" type were used at the high shear stresses locations to measure the strains in three directions in the web. Other demec point stations were located at the mid-span zone to measure the strain distribution along the section. The two external steel strands were released before testing as soon as the machine was in contact with the tested beams.

### 4 Test results

This paper presents the results of three beams tested under static loading conditions. Two of the tested beams were prestressed by 15.2 mm CFCC and reinforced by two different types of CFCC stirrups, 7.5 mm diameter seven wire cables and 5 mm diameter single wire, while the third beam was prestressed by 8 mm Leadline rods and reinforced by Leadline double legged stirrups. All beams behaved linearly up to cracking and after cracking with 70% reduction in the stiffness of the beams prestressed by CFCC and 65% reduction of the stiffness of the beam prestressed by Leadline up to failure as shown in Fig.7. Although the two beams prestressed by CFCC were identical in terms of dimensions, flexural reinforcements and loading conditions, the beam reinforced by the smaller area of stirrups showed slightly more deflection in comparison to the other beam under the same load level. This behaviour may be attributed to the higher shear deformation of the beam with smaller area of stirrups or possible slight difference in the material properties. However both beams with different stirrups sizes showed identical flexural capacity. No slip was observed
for the prestressing strands neither at the end of the beam nor between the girder and the top slab up to failure for all the tested beams.

**Fig.6 Test setup**

**Fig.7 Load-deflection of beams prestressed by CFCC and Leadline**

### 4.1 Mode of failure

The two beams prestressed by CFCC failed by rupture of the lower draped cable at the location of the steel pin, 400 mm outside the constant moment zone, followed by rupture of the three bottom straight cables and finally rupture of the top draped cable as shown in Fig.8. The lower draped cable was 50 mm higher than the bottom straight cables. The rupture of the cables was accompanied by horizontal crack and spalling of the concrete cover along the tendons level due to release of the elastic strain energy after rupture of tendons which is consistent with the findings of the testing done by Abdelrahman and Rizkalla[1]. Failure of the bottom draped cable had occurred before the straight cables, which were located 50 mm lower than the draped one, due to the high localized stress concentration induced at the pin location due to draping.

The beam prestressed by Leadline failed at higher load level in comparison to the beams prestressed by CFCC due to the higher tensile strength of the Leadline. Therefore, the failure occurred by shear at the maximum shear location, 2.6 meters
from the support. Before failure, spalling of concrete cover was observed at the bent of the stirrups from the web to the bottom flange. This behaviour suggests stretching of the stirrups causing spalling of the concrete cover. The brittle failure could be attributed to rupture of the stirrups since the directions of the cracks were with an angle with respect to the direction of the stirrups as shown in Fig.9. The failure of the stirrups caused sudden transfer of forces to the cracked concrete in the web and the prestressing rods resulting in crushing of the concrete and rupture of the rods as shown in Fig.9. The failure may also be caused by straightening of the stirrups at the bent between the web and the bottom flange causing sudden loss of stirrups resistance and transfer of the forces to the cracked concrete and the prestressing rods. The remaining tests will be used to verify the failure mechanism.

![Failure of beam prestressed by CFCC](image1)

Fig.8 Failure of beam prestressed by CFCC

![Failure of beam prestressed by Leadline](image2)

Fig.9 Failure of beam prestressed by Leadline

4.2 Effect of shear reinforcement ratio
The three percentages of shear reinforcement ratio used in this investigation were 0.4, 0.8 and 1.0%, which was achieved by changing the size and the shape of the stirrups. The measured concrete strains in the direction of the stirrups at the maximum shear location for the three types of stirrups is shown in Fig.10. The maximum measured strains in the beams reinforced by CFCC stirrups were 0.45 and 0.82%, where the failure occurred by rupture of the longitudinal prestressing cables. Since Leadline rods have higher ultimate tensile strength than CFCC, failure of beam reinforced by
Leadline stirrups was by shear rather than flexure. The maximum measured strain in the concrete at the location of the stirrups was 0.85% prior to failure. The above suggests that the strength of the stirrups is about 45% of the uniaxial ultimate tensile strength of FRP reinforcement due to inclination of the cracks with respect to the direction of the fibres. The reduction of the tensile strength of the stirrups with the presence of inclined cracks was discussed by many researchers[2].

Fig.10 Concrete strain of the CFCC and Leadline stirrups

5 CONCLUSIONS

The preliminary finding from testing three beams using two different types of CFRP reinforcements could be summarized as follows:

1. Draping of the tendons is feasible for CFRP tendons, however, the residual stresses at the draping points could trigger the flexural failure.
2. Shear resistance of Leadline stirrups is limited to a maximum strain of 0.85% which represent 45% of the uniaxial tensile strain of the reinforcement.
3. Shear failure is very brittle and causes breaking of the beam to several pieces due to the energy released from rupture of the longitudinal prestressing tendons.
4. No slip was observed of the prestressing reinforcement nor between the top slab and the girder. This suggests that the strength of the CFRP stirrups is adequate to transfer the stresses between the top slab and the beam by dowel action.

6 References