First Concrete Highway Bridge in Canada
Prestressed by Carbon Fibre Cables

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SUMMARY

Accepting the challenge of the future in the field of civil engineering smart structure applications, the City of Calgary undertook the responsibility of prestressing six girders of a continuous two span skew highway bridge, using carbon fibre composite cables (CFCC) developed and produced by Tokyo Rope in Japan. This paper describes the construction details used to adopt these new materials into Canadian practices, and an optical fibre sensing system used to monitor the behaviour of the bridge, in addition to conventional electric resistance strain gauges. The paper also discusses the experimental program conducted at the University of Manitoba, Canada, to test a 1:3.3 model of the bridge girders prestressed by CFCC and monitored by the same optical fibre system.

1. GENERAL

Deterioration of concrete members due to corrosion of steel reinforcements is one of the major problems which reduces the service life serviceability of bridges, especially in Canada due to the use of de-icer applications. The cost of correcting corrosion-induced distress in bridges is high compared to the capital cost of the structure. To overcome this problem, the City of Calgary has decided to construct the first concrete highway bridge in Canada using advanced carbon fibre composite cables (CFCC) currently produced by Tokyo Rope in Japan. In addition to their corrosion-resistant characteristics, these material have outstanding characteristics in terms of a high strength to weight ratio, a non-magnetic quality, a high resistance to impact, and an ease of handling and installation due to their light weights.
Various safety precautions and adequate safety factors were used in the design process, in order to satisfy the owner and the building authorities with regards to public safety. The bridge included the state of the art technology of optical fibre sensing systems to monitor the behaviour of the bridge. This paper also describes the experimental program undertaken at the University of Manitoba to test a 1:3.3 scale model of the bridge girders prestressed by CFCC and Leadline rods. The test beams were monitored by electric resistance strain gauges, mechanical gauges, and the same optical fibre sensing system used in the bridge.

2. BRIDGE OUTLINE

The bridge is a two span continuous skew bridge, 22.83 and 19.23 metres, located at Centre Street/Beddington Trail, in Calgary, Alberta, Canada. The bridge consists of a total of 26 bulb-tee section precast prestressed concrete girders, 13 for each span. Each precast concrete girder is prestressed to carry its own weight and the weight of the deck slab. Continuity of the two spans will be achieved by post-tensioning using steel tendons extending along the entire length of the bridge. The 15.2 mm diameter CFCC cables were used to prestress four precast concrete girders, two 22.83 m and two girders of 19.23 m spans. While, the 8 mm diameter Leadline rods were used to prestress two precast concrete girders of 22.83 m span. The six girders are located at the centre of the bridge. The remainder of the precast concrete girders were prestressed using conventional steel strands. Typical concrete pretensioned girders are shown in Figure (1). Dimensions of the cross section are also shown in the same figure.

![Figure 1 Typical girder used for the Calgary Bridge](image-url)
3. DESIGN AND CONSTRUCTION DETAILS OF THE BRIDGE

The flexural design of the girders using carbon fibre reinforced plastics, CFRP, tendons was based on the strain compatibility approach using the material characteristics of the CFCC, Leadline rods and the concrete. The material characteristics of CFRP tendons, as provided by the producer and confirmed by testing at the University of Manitoba, is perfectly linearly elastic up to failure, with a guaranteed tensile strength and elastic modulus of 1750 MPa and 137 GPa, for 15.2 mm diameter CFCC and 1970 MPa and 147 GPa, for 8 mm diameter Leadline rods, respectively. The girders prestressed by CFRP tendons were designed to have an equivalent flexural capacity as the remaining girders prestressed by steel strands. Predicted load-deflection behaviour of the 19.23 metre girder prestressed by CFCC, Leadline and steel strands, subjected to uniform distributed load, are compared in Figure (2). The behaviour of the girders is identical within the service loading range. The girders prestressed by CFCC and Leadline show slightly higher flexural capacity and less deflection at ultimate in comparison to the girder prestressed by steel strands.

![Graph showing load-deflection behaviour of girders](image)

Figure 2 Predicted load-deflection of a girder prestressed by CFRP and steel strands

To adopt the system to the Canadian practice for precasting, steel couplers were used to couple the CFCC and Leadline rods to conventional steel strands, as shown in Figure (3 a,b). The couplers were specially designed by Con-force Structures Company Ltd, Calgary, Alberta, Canada, to match the standard spacing of 50 mm of the prestressing abutments. Details of the wedge system used inside the coupler for the CFCC, Leadline rods and the steel strand is shown in Figure (4 a,b).
Figure 3(a) Steel couplers used for pretensioning CFCC

Figure 3(b) Steel couplers used for pretensioning Leadline
Figure 4(a) Wedge system for CFCC used inside the coupler

Figure 4(b) Wedge system for Leadline used inside the coupler
Due to the high bond characteristics of CFRP tendons, which could result in shorter transfer length and consequently possible split cracking, spiral reinforcements were provided at the end of the girders for each cable. In the unlikely event of any possible distress of the new materials, holes were provided at each thickened end of the girder to allow for external post-tensioning of the girder in this event. Location of the cables at three different layers will also provide significant safety and ductility of the bridge since any possible distress will take place gradually from the bottom layer before it will affect the second and the third layer, therefore providing sufficient warning effect. The bridge behaviour will be evaluated by frequent monitoring using the optical fibre sensing system and the electric strain gauges attached to both CFCC, Leadline rods and steel strands.

4. OPTICAL FIBRE SENSING SYSTEM

State of the art technology of optical fibre sensors were attached to both CFCC and Leadline rods to monitor the girders’ behaviour under various loading conditions. The system consists of intracore Bragg grating optic fibre sensors which relies on the narrow band reflection from a region of periodic variation in the core index of refraction of a single mode optical fibre. The system was designed and installed by the research group of the Institute of Aerospace Studies, University of Toronto. The optical fibres are small in size, have excellent resistance to fatigue and have an extreme sensitivity to measure the small change of strain due to service loading conditions of the bridge. In this sensor, the centre (Bragg) wavelength of the reflected signal is linearly dependant on the product of the scale length of the periodic index variation and the mean core index of refraction. Change of the strain causes shift of the Bragg wavelength leading to a wavelength that can be measured. The two features, among numerous others, make the Bragg sensors especially attractive for strain sensing applications; their immunity to intensity fluctuations and the absolute measurements capability. The measured strains using this system for the beam tested at the University of Manitoba is shown in Figure (5).

![Graph showing load-strain relationship](image)

**Figure 5** Measured load-strain of the test beam using the optical fibre sensing system
5. EXPERIMENTAL PROGRAM

The City of Calgary commissioned University of Manitoba to fabricate four beams, 1:3.3 scale models of the bridge girders prestressed by CFCC and Leadline rods. Two beams, one with CFCC and the other with Leadline, were tested monotonically to failure and the other two beams were subjected to cyclic loading to examine the fatigue failure. The experimental program was undertaken also to gain hands on experience in the prestressing stage for this type of materials. The four beams were prestressed and casted at the Structural Engineering and Construction R&D Facility, University of Manitoba, using the set-up shown in Figure (6) and schematically in Figure (7). The system allowed equal distribution of the total jacking force, using the shown hinge system and load cells to measure the total jacking force. The CFCC and Leadline rods were monitored by electric resistance strain gauges and optic fibre sensors attached to the cables similar to the one used for the bridge.

Figure 6 Prestressing and casting set-up for the test beams
Figure 7 Schematic of prestressing and casting set-up for the test beams

A closed-loop MTS, 1.2 million pounds cyclic loading testing machine was used to apply the load under deflection control, as shown in the test set-up, Figure (8). Deflection at various points was measured using linear variable deflection transducers (LVDT). Demic point stations, to measure the strain in two directions, were used at various locations to determine the strain distribution at the mid span zone and at the end zones.
The other two beams were subjected to a cyclic loading condition with a maximum load equal to the cracking load, and a minimum load level to approximately 70 percent of the cracking load. The beams sustained two million cycles with no sign of reduction in stiffness. After completion of the test, the beams were loaded up to failure; it behaved identically to the beams tested under static loading conditions. The beams failed at a load level of 91.9 kN and 124.2 kN, for beams with CFCC and Leadline, respectively which is 95 and 100 percent of the failure load of the beams tested under static load.

6. CONCLUSIONS

The project described in this paper provided an opportunity to adapt the most advanced composite materials and smart structures technology to the Canadian construction industry. Use of this technology provides a solution to one of the most significant problems related to deterioration of the concrete structures due to corrosion. Use of the advanced optical fibre sensors provided an excellent system to monitor the behaviour of these new materials in the field. The system provides a warning device to measure any possible deficiencies, deterioration or malfunction of these materials during the service life of the bridge. Building a prototype bridge is an essential milestone to the acceptance, continued development and adoption of these types of materials by the construction industry in Canada.
5.1 Test Results

The load-deflection relationship for the tested beams under static loading is shown in Figure (9 a,b). The behaviour indicates a linear relationship up to the initiation of the first set of cracks at a load level of 34.5 kN and 35.2 kN for the beams with CFCC and Leadline rods, respectively. After cracking, the beams behave almost linearly up to failure due to the linear characteristics of the CFRP. The failure was caused by rupture of the bottom tendon at 97.1 kN and 123.3 kN for the beams with CFCC and Leadline rods, respectively, followed by failure of the top tendon. The failure load of the beams was about 30 and 60 percent higher than the predicted, based on the guaranteed strength of the CFRP tendons.

It was decided to unload the beams at a load level approximately equal to 95 % of the predicted failure load, using the guaranteed ultimate strength of the CFCC and Leadline rods, to examine the residual deformations of the beams. It was observed that all cracks were almost closed and the permanent deformation was almost zero, as shown in Figure (9 a,b). The beams also showed the same stiffness during reloading, up to failure. Prior to failure, flexural cracks extended to the top flange of the beams. A major horizontal crack was observed at the onset of failure, which accompanied rupture of the CFRP tendon. No slip was observed during the test up to failure. The cracks were distributed evenly as shown in Figure (10 a,b), with a maximum crack width of 0.8 mm and 1.6 mm, at 85 % of failure load, for beams with CFCC and Leadline rods respectively.
Figure 9(a) Measured and Predicted load-deflection of the test beams prestressed by CFCC

Figure 9(b) Measured and Predicted load-deflection of the test beams prestressed by Leadline
Figure 10(a) Cracks distribution of the beam prestressed by CFCC

Figure 10(b) Cracks distribution of the beam prestressed by Leadline