Abstract
This paper describes an experimental program undertaken at the University of Manitoba to study the serviceability of concrete beams prestressed by carbon fibre reinforced plastic (CFRP) rods. The experimental program consisted of eight concrete beams prestressed by CFRP rods and two concrete beams prestressed by conventional steel strands. The beams were tested using two static concentrated loads which was cycled three times between a lower load level equivalent to 80% of the cracking load of the beam and an upper load level equivalent to 60% of the predicted strength of the beams which is equivalent to 1.5 to twice the cracking load depending on the prestressing level. The beams were tested to examine the various limit states flexural behaviour, as well as to investigate the different modes of failure of concrete beams prestressed by CFRP reinforcement. The parameters considered in this experimental program were the prestressing ratio and the degree of prestressing. The findings of this experimental study, combined with available information, were used to propose design recommendations of concrete beams prestressed by CFRP rods.

Keywords: Beam, bond, carbon, cracking, deflection, FRP, prestressed concrete, serviceability.

1 Introduction
Use of carbon fibre reinforced plastic, CFRP, as prestressing reinforcement for concrete structures, has increased rapidly for the last ten years. The non-corrosive characteristics of CFRP reinforcement significantly increase the service life of the structures. In addition, CFRP prestressing reinforcement has the advantages of a high
strength-to-weight ratio, good fatigue properties and low relaxation losses. However, the low strain at failure and low elastic modulus of CFRP tendons in comparison to conventional steel could significantly affect the structural behaviour and ductility of the structural members in addition to increase of the cost. Ductility of the concrete beams prestressed by CFRP reinforcement could be increased by reducing the jacking stresses and design the beams as partially prestressed concrete members. The advantages of using partially prestressed concrete members, besides its limited camber, is the cost reduction due to the ability to increase the eccentricity of the prestressing reinforcement. However, since the elastic modulus of CFRP prestressing reinforcement is lower than steel, the deformations of members prestressed by CFRP, after crack initiation, will be greater than those prestressed by steel reinforcement. Excessive deflection is not normally recommended since it may cause damage to any attached non-structural elements, ponding or vibration which could affect the member’s serviceability. Deflection greater than 1/250 of the clear span is normally not recommended for the appearance purpose of the structure[1]. Despite the fact that CFRP reinforcements are non-corrosive, large cracks are also not desirable for the structure’s aesthetics. The acceptable crack width could vary for different concrete surface texture and the distance of the cracks from possible observers. It was reported that cracks wider than an average of 0.25 to 0.3 mm could lead to public concern[1]. Therefore, the behaviour of concrete beams prestressed by CFRP reinforcement, in terms of the deflection and cracking is of prime importance.

2 The experimental program

Eight concrete beams prestressed by Leadline CFRP rods, produced by Mitsubishi Kasei, Japan, were tested, in addition to two concrete beams prestressed by conventional steel strands. The beams were 6.2 meter long and 330 mm in depth, having the same span-to-depth ratio typically used for bridge girders. The cross section of the tested beams was T-section with varying flange width from 200 mm to 600 mm as shown in Fig.1. The jacking stresses of the CFRP rods ranged from 50 to 70% of the ultimate guaranteed strength of the Leadline, specified by the manufacturing company. The level of prestressing and consequently the concrete stress distribution along the section was varied by using two and four rods. The distribution of the Leadline rods in the tension zone was also varied to study its effect on the cracking behaviour of the concrete beams prestressed by CFRP rods.

![Fig. 1 Cross section of the tested beams](image-url)
2.1 Material properties
The concrete used for casting the ten beams was provided by a local supplier and the beams were cast 12 hours after jacking. The maximum aggregate size was 14 mm and the measured slump was typically 200 mm. The specified water/cement ratio was 0.37 and the cement content was 400 kg/m$^3$. The mix proportions by weight was 1 (Portland cement) : 2.9 (coarse aggregate) : 1.7 (fine aggregate). Rheobult 1000 superplastisizer with 3 litre/m$^3$ was used to increase the concrete workability. The target compressive strength of the concrete was 30 MPa after 3 days. Twelve concrete cylinders were cast for each patch and were tested in compression before release and at the day of testing according to ASTM C39-86. The elastic modulus as well as the tensile strength of concrete were also evaluated at the day of testing based on ASTM C469-87a and C496-90, respectively. The measured compressive strength of the concrete cylinders varied between 37 to 50 MPa at the time of release and between 47 to 70 MPa at the time of testing. The average elastic modulus was ranging between 29,000 to 38500 MPa, while the average tensile strength, determined from beam test according to ASTM C78-84, was ranging from 5.1 to 7.5 MPa.

The Leadline rods were 8 mm nominal diameter and have an indented shape. The rods were pultruded using linearly oriented Dialead coal tar pitch-based continuous fibre and epoxy resin[2]. The guaranteed tensile strength and elastic modulus of the Leadline rods, specified by the manufacturer based on tension test using steel wedge type anchorage, are 1970 MPa and 147 GPa respectively. The mean tensile strength and the ultimate tensile strain of the Leadline rod are 2250 MPa and 1.3% respectively. The tensile properties of the Leadline were determined at the University of Manitoba using 8 mm rods and 1.2 meter long concrete anchorage. The concrete anchorages were reinforced with steel spirals to prevent bond slippage up to failure. However, it should be noted that failure of the Leadline rod occurred at the face of the concrete anchorage. The average measured tensile stress and strain at ultimate were 2950 MPa and 1.56% respectively. The stress-strain relationship was linear up to 1000 MPa followed by linear response with higher elastic modulus up to failure. This difference in elastic modulus could be due to the effect of misaligning of some carbon fibres which were stretched at a higher stress level causing increase of the elastic modulus. The average measured tensile elastic modulus of the Leadline rods, based on linear regression analysis of the stress-strain relationship up to failure, was 187 GPa.

The bond strength of 8 mm Leadline rod was compared with that of 13 mm steel strand by testing reinforced concrete beams with span of 800 mm and 1200 mm. The measured mean value of the bond stress of Leadline at first slip was 5.0 MPa in comparison to a bond stress of 5.9 MPa of the steel strand. These results suggest that the "flexural bond" strength of the Leadline is less than that of steel strand. This could be attributed to the shape of the 7 wire steel strand which may cause an increase of the bond characteristics due to mechanical interlocking.

2.2 Jacking set-up
The casting bed and the support system used to jacking the Leadline rods for the prestressed beams, is shown in Fig.2. The prestressing forces were applied using four hydraulic jacks, 50 tons capacity each, with locking nuts to maintain the force after jacking. A special system of hinges was used to ensure equal distribution of the
prestressing force to each cable. The total prestressing force was monitored by load cells. Three days after casting the concrete, the prestressing forces were released using the four jacks, two at each end of the beams. Loss of prestressing force was monitored by means of electrical strain gauges mounted on the Leadline rods.

2.3 Test set-up
A closed-loop MTS, 5000 kN cyclic loading testing machine was used to apply the load, as shown in Fig.3. Deflection was measured using linear variable deflection transducers (LVDT) at the mid-span and at the two supports. Demec point stations were used, at various locations, to measure the strains in the concrete in two directions at various limit states. The strain in the FRP rods was monitored by means of electrical strain gauges. Crack width was measured, within the service load range, in the constant moment zone at two levels, at the extreme tension fibre of concrete and at the level of the bottom Leadline rods. A microscope with a magnification factor of 50, moving on a system of rollers, was used to measure the crack width.

The beams were simply supported with 5.8 meter span and 200 mm projection from each end. The beams were tested using two quasi-static concentrated loads, 1.0 meter apart and cycled three times between a lower load level equivalent to 80% of the cracking load of the beam and an upper load level equivalent to 60% of the predicted strength of the beams which is equivalent to 1.5 to twice the cracking load depending on the prestressing level. The aim of the cyclic loading at the service load limit, is to study the deflection, after reduction of the beam stiffness and the cracking behaviour after stabilization of cracks.
3 Transfer length

The transfer length of the 8 mm Leadline rods was determined using the measured strain change of the rods at the end of the beams before and after release of the prestressing force. The strain of the Leadline was measured using strain gauges mounted on the Leadline rods. The data was collected from different beams with the same jacking stresses. The Leadline rods were jacked to 980 MPa for 6 beams, which is 50% of the guaranteed strength, and to 1380 MPa for two beams, which is 70% of the guaranteed strength. The force of the Leadline rods was released gently by releasing the pressure of the jacks, three to four days after casting. The concrete strength ranged between 37 and 50 MPa. The percentage of the strain of the Leadline rods after release compared to the strain before release is shown in Fig.4. The transfer length of the Leadline rods was estimated to be 360 mm, 46 times the rod diameter, when the stress of the Leadline after release was 950 MPa and 500 mm, 64 times the rod diameter, when the Leadline stress after release was 1310 MPa. The average bond strength of the Leadline in the transfer zone was calculated based on the measured transfer length for the two prestress level and was found to be 5.15 MPa. This is comparable to the bond strength of steel strands in the transfer zone which is reported to be 5.21 MPa[3]. This behaviour may be attributed to the lower elastic modulus of the Leadline which cause more longitudinal deformation and consequently more transverse deformation than steel for the same load level, as poisson’s ratio for Leadline and steel are approximately equal. The higher transverse deformations improve the bond strength at the transfer zone due to the lateral expansion of the rod which creates wedge action known by Hoyer effect.

![Fig.4 Transfer length of 8 mm Leadline rod](image)

4 Flexural behaviour of the tested beams

The concrete beams prestressed by Leadline rods behaved linearly up to cracking and linearly after cracking with reduced stiffness up to failure. This is attributed to the linear elastic characteristics of the Leadline rods. Two modes of failure were
observed, rupture of the furthest bottom Leadline rod and crushing of the concrete at the top surface within the constant moment zone. At the onset of rupture of the bottom Leadline rod, a horizontal crack occurred, in some of the beams, at the level of the rod as well as extensive cracks extended to the top flange of the beam. The horizontal cracks occurred due to release of the elastic strain energy after rupture of rods. The released elastic energy which is partly absorbed by the concrete resulted in this extensive cracking at the level of tendons[4]. A progressive failure of the other Leadline rods usually occurred accompanied by horizontal cracks in the constant moment zone. When crushing of concrete occurred, the top steel bars and stirrups were exposed and buckled including the welded wire fabric which was used to reinforce the top flange. Cracking of the beams occurred before crushing of concrete was not as extensive as the cracks occurred for the beams failed by rupture of the Leadline rods. No slip of the Leadline rods was observed to any of the tested beams. Fig.5a and b show the two types of failure for two of the tested beams.

Table 1 shows the cracking load, deflection at first cracking, ultimate load, deflection at ultimate and mode of failure for all the tested beams. The designation of the beams have the first letter either T, R, or S, which refers to T-section of 600 mm flange width, Rectangular section with flange width of 200 mm and Steel reinforcement respectively. The first number of the beam designation is either 2 or 4 which refers to the number of prestressing rods, while the second number, .5 or .7, refers to the ratio of the jacking to the ultimate guaranteed stress. The last letter in the beam designation, H or V, refers to the configuration of the bars in the tension zone, either Horizontal or Vertical. Based on the flexural capacity of the beams, the tensile strength of the Leadline rods was calculated as shown in Table 1. The mean tensile strength of the rods was 3230 MPa with a standard deviation of 100 MPa.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Cracking load (kN)</th>
<th>Deflection at cracking (mm)</th>
<th>Ultimate load (kN)</th>
<th>Deflection at ultimate (mm)</th>
<th>Failure mode</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-4-.5-H</td>
<td>25.31</td>
<td>5.23</td>
<td>106.1</td>
<td>176.5</td>
<td>R</td>
<td>3140</td>
</tr>
<tr>
<td>R-4-.5-H</td>
<td>23.40</td>
<td>7.96</td>
<td>89.3</td>
<td>168.0</td>
<td>C</td>
<td>-</td>
</tr>
<tr>
<td>T-4-.5-V</td>
<td>27.33</td>
<td>4.75</td>
<td>97.9</td>
<td>171.4</td>
<td>R</td>
<td>3270</td>
</tr>
<tr>
<td>R-4-.5-V</td>
<td>23.16</td>
<td>6.37</td>
<td>90.2</td>
<td>186.2</td>
<td>R</td>
<td>3050</td>
</tr>
<tr>
<td>T-4-.7-V</td>
<td>37.90</td>
<td>6.93</td>
<td>102.2</td>
<td>140.1</td>
<td>R</td>
<td>3260</td>
</tr>
<tr>
<td>R-4-.7-V</td>
<td>32.10</td>
<td>8.62</td>
<td>98.1</td>
<td>164.5</td>
<td>R</td>
<td>3215</td>
</tr>
<tr>
<td>T-2-.5-V</td>
<td>13.08</td>
<td>2.55</td>
<td>56.3</td>
<td>151.0</td>
<td>R</td>
<td>3270</td>
</tr>
<tr>
<td>R-2-.5-V</td>
<td>12.69</td>
<td>3.46</td>
<td>56.8</td>
<td>164.6</td>
<td>R</td>
<td>3175</td>
</tr>
<tr>
<td>S-T-2.5</td>
<td>30.71</td>
<td>5.74</td>
<td>77.1</td>
<td>346.4</td>
<td>R</td>
<td>-</td>
</tr>
<tr>
<td>S-R-2.5</td>
<td>27.86</td>
<td>7.04</td>
<td>70.1</td>
<td>170.6</td>
<td>C</td>
<td>-</td>
</tr>
</tbody>
</table>

"R" refers to rupture of the prestressing rod (or strand)
"C" refers to crushing of concrete at the top surface of the beam
4.1 Load-deflection relationship
A comparison of the load-deflection of beams prestressed by Leadline and steel strands is given in Fig.6. In general, beams prestressed by Leadline have stiffness equivalent to beams prestressed by steel before cracking and reduced stiffness after cracking due to the smaller elastic modulus of the Leadline. For beams with 600 mm flange width, the mode of failure was due to rupture of the prestressing reinforcement. The ultimate load of the beam with Leadline was 37% higher while the deflection at ultimate was 50% less than the beam with steel. For beams with 200 mm flange width, the mode of failure was due to crushing of the concrete. The ultimate load of the beam prestressed by Leadline was 27% higher and the deflection at ultimate was equal to the deflection of the beam prestressed by steel.

Beams prestressed by Leadline jacked to 70% of the guaranteed strength had 4 to 8% higher ultimate load than beams prestressed by Leadline jacked to 50% of the guaranteed strength. The deflection at failure was about 11 to 18% less than beams jacked to 50% of the guaranteed strength.

4.2 Strain distribution
The maximum strain of the Leadline, measured at flexural failure, was 1.85%. Based on average value of the measured strains, the neutral axis depth of beams prestressed by Leadline and steel is shown in Fig.7. It can be noticed that the neutral axis shifts towards the compression zone by the increase of the applied load. For beams prestressed by Leadline, the neutral axis depth decreases more rapid than beams prestressed by steel. This is attributed to the lower elastic modulus of the Leadline than steel. Thus, for a given concrete strain in the extreme compression fibre, more strain will be developed in the Leadline in comparison to steel to achieve the same resistance. This behaviour will lead to smaller compression zone depth for beams prestressed by Leadline than beams prestressed by steel subjected to the same load.
As the load increases the neutral axis continues to move causing reduction of the compression zone depth for beams prestressed by steel, while it remains nearly stationary for beams prestressed by Leadline. At yielding of the steel strands, the increase of the internal moment resistance due to the increase of the applied load could be achieved only by increasing the internal lever arm length and consequently the decrease of the compression zone depth. For the case of Leadline, the increase of the internal moment resistance is achieved by an increase of the tensile resultant force due to increase of Leadline stress and therefore the neutral axis will remain nearly stationary up to the rupture of the rod.

4.3 Crack pattern and crack width
Test results indicated stabilization of the flexural cracks of beams prestressed by Leadline rods at significantly lower strain level than beams prestressed by steel. Stabilization of crack pattern is defined by the stage when the number of cracks did
not increase by increasing the applied load[5]. The number of cracks of all the tested beams is shown in Fig.8 in relation to the strain in the prestressing reinforcement after decompression. The smaller number of cracks in beams prestressed by Leadline could be attributed to the lower bond strength of the Leadline than steel in the flexural zone. Stabilization of cracks occurred at an average strain value of 0.001 for beams prestressed by Leadline in comparison to a strain value of 0.0038 for beams prestressed by steel strands.

The relationship between the maximum, minimum and average crack width, \( w_{\text{max}} \), \( w_{\text{min}} \) and \( w_{\text{avg}} \), respectively, is shown in Fig.9, for all the cracks at different load levels of beams prestressed by Leadline. The average values of the ratios \( w_{\text{max}}/w_{\text{avg}} \) and \( w_{\text{min}}/w_{\text{avg}} \) were 0.8 and 1.19, respectively for beams prestressed by Leadline, and 0.56 and 1.60, respectively for beams prestressed by steel. The large variation of the crack width of beams prestressed by steel is attributed to the significant variation of the crack spacing before stabilization of cracks.

Fig.8 Number of cracks of beams prestressed by Leadline and steel

\[
\begin{align*}
\text{Number of cracks} & = 12 \\
\text{Strain} & = 0.000, 0.0001, \ldots, 0.008
\end{align*}
\]

Fig.9 Variation of the crack width of beams prestressed by Leadline

\[
\begin{align*}
\text{minimum and maximum crack width (mm)} & = 0, 0.2, 0.4, 0.6, 0.8, 1 \\
\text{Average crack width (mm)} & = 0, 0.2, 0.4, 0.6, 0.8
\end{align*}
\]

\( w_{\text{max}} = 1.19 w_{\text{avg}} \) \\
\( w_{\text{min}} = 0.8 w_{\text{avg}} \)
Table 2 Maximum Leadline and steel stress to control crack width

<table>
<thead>
<tr>
<th>Crack width (mm)</th>
<th>Maximum Leadline stress (MPa)</th>
<th>Maximum Leadline strain</th>
<th>Maximum steel stress (MPa)</th>
<th>Maximum steel strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>130</td>
<td>0.0009</td>
<td>150</td>
<td>0.0008</td>
</tr>
<tr>
<td>0.2</td>
<td>210</td>
<td>0.0014</td>
<td>240</td>
<td>0.0013</td>
</tr>
<tr>
<td>0.3</td>
<td>280</td>
<td>0.0019</td>
<td>320</td>
<td>0.0017</td>
</tr>
<tr>
<td>0.4</td>
<td>360</td>
<td>0.0024</td>
<td>390</td>
<td>0.0021</td>
</tr>
</tbody>
</table>

In partially prestressed beams, the desired crack control could be achieved by limiting the increase in the stress of reinforcement after decompression. The limiting values of the Leadline stress and corresponding strain are compared to that of prestressing steel, obtained from reference [6], in Table 2. It can be seen that the maximum strain for a given crack width is the same for both steel and Leadline rods.

5 Summary and conclusions

Eight concrete beams prestressed by Leadline CFRP rods were tested to investigate the flexural behaviour of such beams. The following conclusions can be drawn:

1. The flexural bond strength of the Leadline is less than that of steel strands, however the bond of the Leadline at the prestress transfer zone is comparable to that of steel strands due to Hoyer effect.
2. The stabilized crack pattern is obtained at a much lower strain for beams prestressed by Leadline rods than beams prestressed by steel strands.
3. The number of cracks of beams prestressed by Leadline is less than that of beams prestressed by steel strands due to the lower flexural bond strength of the Leadline rods.
4. The strain resulting in a given crack width is the same for beams prestressed by Leadline and steel.

6 References