Concrete Beams Strengthened with Misaligned CFRP Laminates

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ABSTRACT
A unidirectional carbon fiber reinforced polymer (CFRP) laminate has its maximum strength and stiffness in the fiber direction. However, misalignment of fibers can be introduced intentionally or unintentionally during design or construction of structures. In this paper, the effect of fiber misalignment on the performance of concrete beams strengthened with CFRP laminates is experimentally investigated. Five unreinforced concrete Tee beams were cast and strengthened with CFRP laminates. The laminates had an off-axis angle of 0, 2, 5, 8, and 10°, respectively. The beams were tested under four-point loading to total failure. The objectives of this research were to investigate (1) strength and stiffness of beams, (2) strain distribution of CFRP laminates and, (3) failure modes. It was found that the variation of beam capacity with the severity of misalignment showed a different trend from that of midspan deflection and that failure by rupture of the CFRP laminate was experienced by all beams. A bond length of 127 mm was sufficient to develop the strength of the CFRP laminate.

INTRODUCTION
Composite materials are generally applied in the optimal direction so their performance (stiffness and strength) can be well developed. However, it is unavoidable that FRP may not be applied in the exact direction as expected and some misalignment may exist. The misalignment can be introduced unintentionally by errors in design and construction or intentionally by the restriction in the structure’s geometry. Because FRP laminates are orthotropic materials, the maximum stiffness and strength are exhibited along the fiber direction. Any deviation from this direction will cause strength and stiffness degradation. The influence of this degradation needs to be investigated to obtain an accurate evaluation of the performance of strengthened structures. The ultimate goal of this investigation is that the effect of misalignment on stiffness and strength degradation be implemented into design and analysis. M'Bazaa(1996) tested three RC beams strengthened with two symmetric misaligned CFRP plies and one CFRP ply in the direction of the longitudinal axis of the beam. The results indicated that the strength and deflection did not change significantly compared with the beams strengthened with three CFRP plies having fibers applied with the longitudinal beam axis. There is no other literature available on the subject.
In this paper, five 1.22 m plain concrete beams were constructed and strengthened with one ply of misaligned CFRP laminate. The beams had a saw-cut crack at the midspan of the tension face and a fixed hinge was installed at the midspan of the compression face. After cracking of concrete at the center, only the CFRP laminate sustained the tension force, which allowed to investigating the performance of the laminate, to determine the strain distribution, and to identify the effective bond length.

Before testing the concrete beams, CFRP laminate coupons consisting of one and two-plies were tested to investigate the strength and stiffness degradation with misalignment. All coupon specimens had an aspect ratio of 4 and a width of 38 mm. The specimens were tabbed at both ends and tested in an MTS 880 testing machine. For the two-ply laminates, one ply was oriented in the loading direction and the other ply was oriented at angles ranging from a minimum of 0-deg to a maximum of 90-deg. Coupon size effect on the strength and stiffness of misaligned CFRP laminates was addressed by making samples with the same width but different aspect ratios ranging from 2 to 8 until no through fibers existed between end tabs (Yang et al. 2000). This paper only reports part of the results of the entire project.

**EXPERIMENTAL PROGRAM**

**Material Properties**
The design properties of carbon fiber and saturant are listed in Tables 1 and 2 as provided by the manufacturer (MBrace, 1998).

The CFRP system was applied to the beam tension surface with a hand lay-up technique according to the procedure specified by the manufacturer. After the concrete surface was sandblasted and cleaned by pressure air, a thin layer of primer was applied to the surface using a roller. Following the application of the primer, putty was applied to the areas with small holes in order to smooth the concrete surface. Then the first layer of saturant and fiber ply were applied when the primer was still sticky. After smoothing the ply into the saturant with a nap roller, a second layer of saturant coat was applied to obtain thorough epoxy impregnation.

<table>
<thead>
<tr>
<th>Table 1 Mechanical properties of CF130 tow sheet</th>
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<tbody>
<tr>
<td>Ultimate strength</td>
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<tr>
<td>Design strength</td>
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<tr>
<td>Yielding modulus</td>
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<tr>
<td>Ultimate strain</td>
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* results from coupon tests (Yang et al. 2000)

<table>
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<tr>
<th>Table 2 Mechanical properties of MBrace saturant</th>
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<tbody>
<tr>
<td>Maximum stress</td>
</tr>
<tr>
<td>Maximum strain</td>
</tr>
<tr>
<td>Yielding strain</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
</tr>
</tbody>
</table>
Concrete cylinders were tested showing concrete strength of 24.96MPa to 38.24MPa. Miller (1999) indicated that concrete strength does not play a critical role on bond strength of CFRP laminates on concrete and only affects the cracking load. The ultimate load was controlled by the CFRP strength and bond strength. This conclusion was justified by the results of current research, where all beams experienced the same failure by rupture of the CFRP laminate regardless of concrete strength.

**Specimens and Test Setup**

Five plain concrete inverted Tee beams were constructed with dimensions as shown in Figure 1. A 51mm-deep artificial crack was cut at the center of the tension face. A steel hinge was installed into a 51mm-deep saw-cut groove at the center point of the top compression surface. After cracking of the beam, the force was sustained by the CFRP laminate only to facilitate the evaluation of the bond characteristics between CFRP laminate and concrete substrate. After cracking, a constant moment arm of 222 mm was produced from the center of steel hinge to the CFRP laminate.

![Fig. 1 Specimen and strengthening (Unit: mm)](image-url)
The bond length of the CFRP laminate was 203 mm. There was an unbonded area of 51 mm at both sides of the artificial crack to prevent stress concentration at the center point. A 203 mm wide lateral anchor laminate was installed at one end of the beam to force failure of the opposite side.

The beam was tested under four-point loading. Midspan deflection and strains along the fiber directions were collected with LVDT and strain gauges, respectively. Strain gages were attached along the fiber direction (Figure 2).

**TEST RESULTS**

**Strength and Deformation**

Figure 3 shows the load versus midspan deflection for all five beams. Before cracking, beams had different stiffness and cracking loads due to the different concrete strength. At this stage, the contribution of CFRP is negligible. After cracking, the load decreased with different slopes but converged to a point with a load and deformation of 7.5 kN and 0.7 mm, respectively. The measured strain on the surface of the CFRP laminate within the central unbonded area was around 0.4%. After this point, the response of the beam entered the second stage, when only the CFRP laminate carried the tension force until failure and the compression force acted in the center of the steel hinge.

**Fig. 3 Load-midspan deflection of all beams**
Figure 3 shows that the beam with 0-deg CFRP laminate had a higher ultimate load from the beginning of the second stage while all other four beams did not show much difference in ultimate load and response. The individual ultimate load and midspan deflection are listed in Table 3 and plotted in Figures 4 and 5 versus the misalignment angle. Except for the ultimate load of the 2-deg beam that decreased by 18.2% compared with that of the 0-deg beam, all of the other four beams had a negligible difference in ultimate load. The change of midspan deflection shows a little difference from that of ultimate load. The 0-deg and 2-deg beams had the same maximum deflection. The deflection of the 5-deg beam was only 10.0% less than that of the 0-deg beam. For misalignment angles larger than 5 degree, the midspan deflection decreased significantly. The deflection of 8-deg and 10-deg beams decreased 25.0% compared with the 0-deg beam.

The change of midspan deflection actually reflects the trend of the stiffness degradation of misaligned CFRP laminates from the tensile coupon tests (Yang et al. 2000). The modulus of elasticity of 0, 5, and 10-deg coupons and the normalized average modulus of laminates from these beam tests is depicted in Figure 6. When the misalignment angle is less than 5 degree, the modulus of elasticity does not degrade. After the angle exceeds 5 degree, the modulus degrades rapidly. The modulus degradation of CFRP laminates shows the same trend of the coupon tests.

<table>
<thead>
<tr>
<th>Angle (deg)</th>
<th>Ultimate load (kN)</th>
<th>Maximum midspan deflection (mm)</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>26.43</td>
<td>5.10</td>
</tr>
<tr>
<td>2</td>
<td>21.62</td>
<td>5.10</td>
</tr>
<tr>
<td>5</td>
<td>21.23</td>
<td>4.55</td>
</tr>
<tr>
<td>8</td>
<td>22.27</td>
<td>3.84</td>
</tr>
<tr>
<td>10</td>
<td>21.48</td>
<td>3.76</td>
</tr>
</tbody>
</table>

Fig. 4 Degradation of ultimate load deflection

Fig. 5 Degradation of midspan deflection
Fig. 6  Modulus degradation of tensile coupons and beams

**Strain Distribution and Failure Modes of CFRP Laminates**

Figure 7 shows the typical strain distribution for CFRP laminates along the fiber direction. The strain gage positions were measured from the center of the beam, which is also the center of the unbonded area. It is assumed that the strain in the laminates within the unbonded area is constant.

Figure 7 also shows that the effective bond length of CFRP laminate when delamination first occurred is independent of other parameters such as concrete strength and surface condition. All five beams have an effective bond length of 127 mm.

All beams failed with rupture of CFRP laminate within the delaminated area. Figure 8 shows that the CFRP laminate of the 0-deg beam pulled off less concrete and had a smoother surface than that of the CFRP laminate of 10-deg beam.

Fig. 7  Strain distribution of all beams
Fig. 7 Strain distribution of all beams (cont.)

Fig. 8 Delamination of CFRP laminates
CONCLUSIONS
Based on the experimental investigation of concrete beams strengthened with misaligned CFRP laminate, the following conclusions can be reached.

• The change of strength and deformation with misalignment shows different trends. When the misalignment angle is small (less than 5 degree), the strength of the beam is not affected. The deformation decreases very slowly at first, and then more rapidly with increasing misalignment, which agrees with the stiffness degradation of CFRP laminate with misalignment.

• Rupture of CFRP laminates is the controlling failure mode if the concrete surface is properly prepared. Delamination occurs in the CFRP laminates but it is not the controlling failure mode.

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