DEFLECTION OF GFRP AND PVA FIBRE REINFORCED CONCRETE BEAMS

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Abstract

There is an increasing demand for the use of Fibre Reinforced Polymers (FRP) in Reinforced Concrete (RC) design for various reasons, including electromagnetic neutrality and corrosion resistance. Glass fibre reinforced polymer (GFRP) reinforcing bars are one such alternative to steel reinforcement. Compared with steel, GFRP bars behave linearly elastic up to failure and do not yield, which can cause ductility concern. To compensate for this, the addition of polyvinyl alcohol (PVA) fibres to the concrete mix can improve the ductility response of RC members through improved post-cracking performance. This post-cracking performance is improved by two mechanisms: in the compression region fibres act to restrain concrete crushing, and delay failure, and in the tension region fibres transfer tensile stresses across cracks. This paper reports on an experimental study on the influence of fibre content on the deflection and energy absorption capacity of RC beams, and presents a structural mechanics based model for evaluating the deflection GFRP FRC members. The theoretical load-deflection responses are compared to the experimental results, showing very good approximation of both the ultimate flexural capacity and the ductility of PVA fibre reinforced concrete members. The good correlation with experimental results confirms the applicability of this structural mechanics based approach in predicting deflections of RC members, and provides engineers with a useful tool to evaluate the ductility and energy absorption capacity of fibre reinforced concrete beams.

Keywords: deflection, ductility, PVA fibres, sand coated GFRP bars, stress-crack width
1. Introduction

The use of non-metallic materials in structural design is increasing in popularity due to their advantages in highly corrosive environments and situations where electromagnetic neutrality is important. Glass Fibre reinforced polymer (GFRP) reinforcing bars are one such alternative to steel reinforcement. Compared with steel, GFRP bars behave linearly elastic up to failure and do not yield, providing concerns regarding ductility compared to the use of steel reinforcement. To compensate for this, the addition of polymer fibres to the concrete mix can improve the ductility response of RC members through enhanced tensile post-cracking performance and delayed compression failure. Research into Fibre Reinforced Concrete (FRC) undertaken by Wang et al. (2005) concluded that FRC beams fail in a more ductile way than standard reinforced concrete (RC) beams, with the load carrying capacity reducing less rapidly once the ultimate concrete strain is reached. Despite the significant benefits of adding fibres to RC members, there are currently few design codes which are capable of quantifying the impact of fibres on the load-deflection response of RC members.

This paper reports on the development of a generic structural mechanics based model that simulates the load-deflection behaviour and consequent ductility response of poly vinyl alcohol (PVA) FRC beams. To develop this generic model, the bond-slip relationship (τ-δ) of the GFRP reinforcing bars, the stress-crack width relationship of the PVA fibres, and the sectional moment-rotation (M-θ) response are all required. Both the GFRP reinforcing bar bond slip relationship and the stress-crack width relationship of the PVA fibres were extracted from experimental tests, and a theoretical moment-rotation response was used to predict the ductility of a PVA FRC beam and compared to experimental load-deflection responses.

2. Experimental Program

In order to develop a structural mechanics based model which can incorporate fibres, two key material properties are initially required: the unique bond-slip relationship of the GFRP bars in fibre reinforced concrete, and the tensile stress-crack width relationship of PVA FRC. However, only the influence of fibre content on the bond properties of the sand coated bars is reported here due to size limitations.

2.1 Material Properties

The bond (τ-δ) properties of the sand-coated GFRP bars were determined from pull-tests. These properties are required for subsequent use in the moment-rotation analysis. The influence of varying fibre content on the bond properties of the sand coated GFRP bars was determined, where three different fibre contents were considered: 0 kg, 6 kg and 12 kg per cubic metre of concrete. All other properties were constant, such that the effect of increasing fibre content on the bond capacity of the bars could be isolated. The average P- Δ response for varying fibre content is shown in Figure 1, where the length of embedment was 60mm. Experimentally, the specimens shown in Figure 1 all failed by pull-out of the reinforcing bar. Pullout failure occurred once the shear strength of the bond between the rebar and concrete was exceeded and at this point the bar began to pull out.
The local bond-slip relationship of the sand coated GFRP reinforcing bars was determined from the experimental load-deflection (P-Δ) responses in Figure 1. The local bond-slip response can be determined directly from short embedment length tests since the variation of slip along the bar is minimal, and hence the experimental average bond stress (τ_{av}) and slip is approximately equal to the local τ-δ relationship required.

For all fibre contents, a similar ascending branch and peak load were observed. However, the GFRP bars in the FRC displayed a steeper ascending branch compared to the ordinary concrete, where a stronger bond was present for smaller slips. Post peak load, the FRC specimens had a slightly reduced load for a given slip compared to the ordinary concrete specimens. Using the experimental P-Δ relationship above, the local bond-slip relationship of the sand coated GFRP bars was determined with the use of a numerical technique (Haskett et al 2007). It was found that for a parabolic ascending and a linear descending τ-δ relationship best fitted the experimental data. Key values describing the τ-δ behaviour are presented in Table 1. These material properties in Table 1 and are used later to develop a moment-rotation response.

### Table 1: Bond-Slip Relationships

<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>0 kg/m³</th>
<th>6 kg/m³</th>
<th>12 kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Bond (MPa)</td>
<td>14.4</td>
<td>14.1</td>
<td>13.2</td>
</tr>
<tr>
<td>Slip at Max Bond (mm)</td>
<td>0.35</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>Slip at Debonding (mm)</td>
<td>8.67</td>
<td>7.00</td>
<td>3.53</td>
</tr>
<tr>
<td>Ascending Slope Factor</td>
<td>0.31</td>
<td>0.29</td>
<td>0.32</td>
</tr>
</tbody>
</table>

#### 2.2 Beam tests

In order to validate our theoretical moment-rotation model presented later, four 1800 mm long reinforced concrete beams were tested to failure in flexure, and the experimental load-mid-span deflection was recorded. The only variable in these beam tests was the fibre content: two beams had 6kg of fibre per m³ of concrete and the final two beams had 12kg of fibre per m³ of concrete. A summary of the results from the experimental tests is provided in Table 2.
Table 2: Beam failure load and deflection

<table>
<thead>
<tr>
<th>Beam (Fibre kg; Beam No.)</th>
<th>Peak Load (kN)</th>
<th>Mid-span deflection at peak load</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>6F B1</td>
<td>160.57</td>
<td>17.6</td>
<td>Web-shear</td>
</tr>
<tr>
<td>6F B2</td>
<td>179.21</td>
<td>25.5</td>
<td>Concrete Crushing</td>
</tr>
<tr>
<td>12 FB1</td>
<td>169.07</td>
<td>22.7</td>
<td>Concrete Crushing</td>
</tr>
<tr>
<td>12 FB2</td>
<td>181.41</td>
<td>22.3</td>
<td>Concrete Crushing</td>
</tr>
</tbody>
</table>

An example cracking pattern at failure for beam 12FB1 is shown in Figure 2. This mode of failure shown in Figure 2 is consistent with that reported by Benmokrane et. al. (1995) where a wedge forms in the compression zone, and flexural cracking commences in the tensile region and ultimately joins the bottom of the wedge, causing failure.

Figure 2: 12FB1 Cracks at failure

After each test the experimental crack patterns were recorded and the crack spacing was also measured and recorded. Using the observed loads, initial ‘primary’ tensile cracks and subsequent ‘secondary’ cracks were observed and their spacings measured. The average crack spacing is summarised in Table 3, where these experimental crack spacings are compared to predicted crack spacings from a tension stiffening analysis and used in the theoretical analysis.

Table 3: Crack spacing

<table>
<thead>
<tr>
<th>Beam</th>
<th>No. Cracks</th>
<th>Primary Crack Spacing (mm)</th>
<th>Secondary Crack Spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6FB1</td>
<td>14</td>
<td>76.4</td>
<td>34.3</td>
</tr>
<tr>
<td>6FB2</td>
<td>22</td>
<td>76.0</td>
<td>39.6</td>
</tr>
<tr>
<td>12FB1</td>
<td>23</td>
<td>80.3</td>
<td>40.4</td>
</tr>
<tr>
<td>12FB2</td>
<td>25</td>
<td>81.7</td>
<td>34.0</td>
</tr>
</tbody>
</table>

3. Theoretical analysis – tension stiffening mechanism

To simulate the partial interaction behaviour of the tension reinforcement, the unique bond-slip relationship of the GFRP bars is used in a tension stiffening analysis. This analysis quantifies the tensile force in the bar for a given crack width, the load to cause further cracking in the concrete, and the distance between adjacent cracks. A numerical model was developed where at the crack face there is slip between the concrete and the bar. For this slip, the bond-slip relationship quantifies the magnitude of the shear stress that can be transferred from the bar to the concrete. This transfer of stress from the bar to the concrete reduces the force in the bar, increases the force in the concrete and reduces the slip of the bar relative to the adjacent concrete along the length of the concrete prism away from the crack face. At some point along the length of the bar both the slip and the slip-strain, which is simply the difference in strains between the bar and the concrete, reduce to zero. This indicates the
position of full-interaction between the bar and the concrete, and therefore for a given crack-
face slip, the load in the bar is known. A primary crack then develops when the stress in the
concrete approaches the tensile cracking stress at the position of full interaction. From this
analysis the load and spacing at which primary cracks form can be determined. The loads at
which secondary cracks form (if applicable) can also be determined, where by symmetry
these cracks form at half the primary crack spacing. Knowing the locations of cracks, and the
moments at which these cracks form is required for later use in the load-deflection analysis.

3.1 Prism Size
As the stress in the concrete is dependent on the assumed size of the concrete surrounding the
bar, the prism size is of critical importance. To calibrate the theoretical prism size, the loads at
which cracks developed experimentally in the beam tests were recorded and the theoretical
prism size used in the tension stiffening model was modified to produce a similar result. Using
the experimental strain profile of the beam, the force in a bar at the load at cracking
was found. From this force, the prism size of the tension stiffening model was changed to also
produce cracking at this load. This was necessary as conventional methods under predicted
the load at which cracking formed and subsequently would under predict the crack spacing.
Additionally, this behaviour is extremely sensitive to the material properties of the concrete;
the asymmetric cracking pattern and strain profiles taken from both sides of the beam
experimentally highlighted the variability of results that can occur.

3.2 Addition of fibres
The addition of fibres to concrete is known to create more cracks, but at the same time
restrain the widening of these cracks. To simulate this behaviour, the stress-crack width
properties of the PVA fibres were required. This material property was determined
experimentally (and not reported here), and used in the theoretical analysis to impose an
initial tensile stress in the concrete at the crack face. This produced some initial tensile
concrete stress in concrete at the crack face and resulted in slightly reduced crack widths and
smaller crack spacing; more so for the higher 12 kg/m³ mix. For example, the addition of
PVA fibres introduces an initial tensile stress at the crack face (approx. 6% of fᶜ), and reduces
the primary crack spacing by approximately 10%. Using the calibrated prism size, the stress-
width behaviour of the fibre concrete, and the bond-slip relationships for the specific
mixes, the crack spacing produced from the model were within the range observed in the
beam specimens. Having modelled the partial interaction behaviour of the GFRP bars and
simulated crack formation, the moment-rotation response of a FRC beam can be determined.

4. THEORETICAL ANALYSIS – MOMENT ROTATION RESPONSE
In order to model the M-θ relationship of fibre reinforced concrete beam, a mechanics based
M-θ model developed by Visintin et.al. (2011) was adapted to incorporate the effects of
fibres. These fibres bridge tensile cracks, and provide additional tensile capacity once
cracking occurs compared to conventional concrete, and also delay compression failure by
confining the compression wedge once it has formed. Other than these two fibre specific
properties, the analysis procedure is identical to that reported by Visintin et al. (2011).
4.1 Effect of FRC on concrete compression wedge

Fibres within the concrete matrix act to confine the compressive concrete (Wang et al. 2005). To incorporate this effect of fibres; an additional stress across the sliding plane of the compression wedge was introduced to account for the confining effects of the fibres. In the absence of any experimental tests, and for simplicity, it was assumed that the fibres provided additional confinement to the crack face equal to the post cracking tensile capacity of the fibres from stress-crack width relationships (Lee et al. 2011).

4.2 Theoretical model and validation

The addition of fibres to the concrete matrix increases the post-cracking tensile strength of the member. Using experimentally obtained stress-crack width relationships from previous experiments (Lee et al. 2011) the stress that the PVA fibres transmit across a crack can therefore be quantified and included in the model. The inclusion of fibres was shown to only marginally increase the flexural capacity of the section.

To validate the moment-rotation analysis, theoretical load-strain and load-crack width distributions were compared to experimentally obtained values. Both strains and crack widths under increasing load were compared and showed good agreement with the experimental results, as shown in Figure 3. Owing to size restrictions, other validations have not been shown, however all comparisons between experimental and theoretical behaviour indicate the accuracy of the theoretical model in both the pre-peak and post-peak load range where the crack face starts to close.

![Figure 3: Load bottom crack profile 12FB2](image)

5. THEORETICAL ANALYSIS - LOAD DEFLECTION MECHANISM

Having developed a theoretical moment-rotation relationship and knowing the loads in the reinforcement when secondary cracks develop, a member analysis can be performed and the theoretical and experimental load-deflection relationships compared. The Load-Deflection analysis involved predicting the gradual formation of cracks along the member length for increasing load by considering two distinct regions of a beam, namely the disturbed region, where tensile cracks have formed and the undisturbed region which remains uncracked. The
applied loads at which these cracks formed and the positions of any subsequent cracks were predicted using the tension stiffening analysis described earlier. At each crack position the load and hence moment is known and therefore the theoretical rotation at that position is also known from the moment-rotation analysis described earlier. Knowing the rotation at each crack position the deflection due to the formation of discrete cracks can be determined, and over the undisturbed region, where the moment is less than the moment to cause a primary crack, the deflection due to curvature can be determined through integration. As the applied load increases and cracks form, the relative contribution of the cracks to the total deflection increases at a much faster rate than that due to curvature. This effect decreases with increasing fibre content due to the additional fibres acting to resist the crack opening, resulting in smaller crack rotations for a given moment. Experimentally and theoretically, low deflections correspond to small and crack widths and hence the fibres make minimal difference initially. Once the concrete begins to crush (what we refer to as soften) the fibres restrain and delay this form of failure and provide increased energy absorption capacity for increasing fibre content. This is a significant benefit of the addition of fibres to concrete which is often overlooked.

5.1 Load-Deflection Comparisons

A comparison of the theoretical and experimental Load-Deflection relationships is shown in Figure 4 for 12kg/m³ of PVA fibre. At the commencement of the post-cracking range there is a noticeable decrease in slope for both the experimental and theoretical Load-Deflection curves. This is due to the cracks now contributing to the overall deflection of the member through discrete rotations. As the load continues to increase, further cracking occurs, resulting in further decreases in slope. This is modelled theoretically and simulates the experimental behaviour. As the experimental curve approaches peak load, the modelled curve begins to deviate, exhibiting greater ductility post-peak than the theoretical Load-Deflection response. This is due to the manner in which the concrete softening mechanism was simulated, where in the absence of experimental tests on the compression softening properties of concrete; an approximate confining stress was imposed on the softening concrete. Clearly more experimental testing on the softening behaviour of PVA reinforced concrete is required to simulate theoretically this more gradual reduction in load for increasing displacements.
From Figure 4 it is clear that this structural mechanics based model can simulate the gradual formation of cracks in a reinforced concrete member and additionally simulate the deflection of a fibre reinforced concrete beam under increasing load.

6. CONCLUSIONS

In this paper the influence of PVA fibre content on the bond properties of sand coated GFRP bars and fibre concrete was discussed. PVA fibres increase the shear stress capacity of the sand coated bar at low levels of slip, but at the same time increasing fibre content reduced the magnitude of the maximum shear stress that could be transferred between the bar and concrete. The influence of fibre content on the loads and spacing of primary and secondary cracks was also discussed, where the inclusion of fibres provided marginally smaller crack spacing and a corresponding reduction in the load in the reinforcing bar when these cracks occurred.

A moment-rotation model was presented which considered the beneficial properties of the PVA fibres in delaying compression failure of the concrete and allowed for the tensile stresses that the fibres transfer across crack faces. Comparison between the fibre concrete and ordinary concrete moment-rotation responses indicated that the PVA fibres restrain the growth of all cracks, resulting in smaller crack widths and a corresponding reduction in rotation. For the fibre concentrations considered, the ability of the fibres to transfer stress across the cracked tensile region and restrain the sliding failure in compression resulted in slight increases in the ultimate moment capacities. Finally, a generic structural mechanics based deflection model was developed and the load-deflection results from this model were compared to experimental beam tests. The deflection model developed was able to predict the gradual reduction in strength post-peak load, and also predict the ultimate flexural capacity of the beams. The model simulated the experimental results, where a more ductile failure occurred in beams containing increasing fibre content.

7. REFERENCES