EFFECT OF ADHESIVE THICKNESS ON BOND BEHAVIOUR OF CARBON FIBER SHEET UNDER STATIC AND FATIGUE LOADING

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ABSTRACT

Carbon Fiber Sheet (CFS) is used for reinforcing concrete structures. CFS is useful because it is light, durable, and corrosion resistant. A typical type of fracture in concrete that has been reinforced with Carbon Fiber Reinforced Polymer (CFRP) is caused by sheet debonding, so it is very important to understand the debonding mechanism.

In execution, the thickness of the adhesive layer between CFRP and concrete is controlled by the condition of the substrate concrete interface and the expertise of the workforce. However, there have so far been few studies of the effect of differences in bond thickness on debonding. This study focuses on the effects of varying adhesive thickness from the point of view of static and fatigue debonding strength, taking adhesive thickness and fatigue loading level as test parameters. The fatigue test with adhesive thickness as a parameter seems to be the first of its type in the world.

In the static test, the effects of adhesive thickness are observed in pull-out bond strength and effective bonding length, observed by measuring CFS strain, as predicted by a model in the literature\textsuperscript{1). In the fatigue test, however, the effects of the adhesive layer seem to be different. Proposals are made as to how to consider the effect of adhesive layer thickness in design.

KEYWORDS

Carbon Fiber Sheet (CFS), adhesion, fatigue loading, resin, effective adhesive length

INTRODUCTION

The demand for concrete reinforced with Carbon Fiber Reinforced Polymer (CFRP) sheet is increasing. As a consequence, research into the adhesion of Carbon Fiber Sheet (CFS) has been rapidly increasing, leading to clarification of the bond stress-slip (\(\tau-s\)) relationship and the fracture energy in static loading. On the other hand, the few studies of adhesion characteristics in cyclic loading have not been enough to clarify the mechanism. Cyclic loading has a greater influence in bridge applications, so rapid unravelling of the mechanism is desired. Past research\textsuperscript{1,2) has indicated that the influence of adhesion characteristics increases with adhesive thickness. Adhesive thickness is controlled by conditions at the surface of the substrate concrete. However, there is no reliable and full consideration of the effect of adhesive thickness and if the effect is found to be large, it will be necessary to restrict thickness variation in design.

This paper aims at deeper insight into the effect of varying adhesive thickness under static and fatigue loading. Variations in adhesive thickness are intentionally made large, so specimens are prepared with three thicknesses, 0.2mm, 1mm, and 3mm.

It is also investigated whether pull-out bond strength with rather thick adhesive under static loading matches the prediction by Dai et al’s model\textsuperscript{1).}

EXPERIMENTAL OUTLINE

Test equipment: experiments were carried out on equipment (see Fig. 1) prepared according to Osaka University’s bending machine test setup. The equipment has a centre hinge connecting two wide flanged beams. The specimen is attached to the resulting beam assembly. A load-distributing beam, distributing of loading is connecting to an actuator, applies loading to both of the distribution on the both side wide flanged beams,
causing the central point at the join to open and close around the hinge. This rotation causes a shear stress at the interface between the substrate concrete and the CFS in the CFRP-concrete. The distance between loading points on the upper surface of the beam assembly is 1200mm. The distance between the fixing points below the beam assembly is 600mm. The testing machine is 200mm high.

Specimens: two concrete prisms (length 600mm, section 100×100mm) are aligned longitudinally with a small gap between their end faces. A single-lap CFS is bonded across the top surfaces of the slabs. The CFS is 60mm wide and the area of attachment to each concrete prism is 60×200mm. In order to avoid local damage to the concrete block, an unbonded section (50mm) is ensured by using vinylon tape to separate the concrete surface from the CFS.

In order to ensure debonding on the intended side, the bonded CFRP was covered and glued with a channel steel plate. The gluing resin was the same as the adhesive for CFRP-concrete interface. Moreover, to prevent damage concentrating at the ends of the slabs, the ends of the specimen were reinforced with a L-shaped steel plate. And, the specimen was reinforced with D10 reinforcing bar for longitudinal direction to prevent flexural failure before CFRP debonding and D6 reinforcing bar as additional reinforcement to prevent unexpected cracking.

The ready-mixed concrete used for experiment was made with early strength Portland cement and had a slump of 12cm and a design strength of 30N/mm². The curing period was two weeks.

The resin adhesive was applied as follows. First, a divider was used to encircle the area to be bonded to the intended adhesive thickness. Resin was then poured into the encircled area. Finally, the CFS was impregnated with resin and laid down over the bonding area. The characteristic values of the CFS and the resin are shown in Table 1 and Table 2, respectively. The specimen is shown in Fig. 2.

Measurements: the values measured were CFS strain, acting load, and fatigue life. Strain gauges of length 5mm were attached at intervals of 20mm to the surface of the CFS in the longitudinal direction.

Measurement method: in static loading, the load was adjusted by hand under load control. The above measurements were made. In fatigue loading, the load was adjusted as in the static test up to ten cycles. Beyond ten cycles, the load was controlled automatically, but at measurement points the load was once again hand operated.

<table>
<thead>
<tr>
<th>Properties of CFS</th>
<th>Thickness</th>
<th>Elastic modulus</th>
<th>Tensile strength</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>tf (mm)</td>
<td>Ef (GPa)</td>
<td>(MPa)</td>
<td>(g/m²)</td>
<td></td>
</tr>
<tr>
<td>0.333</td>
<td>245</td>
<td>3400</td>
<td>600</td>
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</table>

<table>
<thead>
<tr>
<th>Adhesive properties</th>
<th>Elastic modulus</th>
<th>Tensile strength</th>
<th>Compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga (GPa)</td>
<td>(MPa)</td>
<td>(MPa)</td>
<td></td>
</tr>
<tr>
<td>593</td>
<td>23</td>
<td>57</td>
<td></td>
</tr>
</tbody>
</table>
ANALYSIS OF TEST RESULTS

STATIC TEST

The relationship between pull-out strength and adhesive thickness is shown in Fig. 3. It can be seen that pull-out strength increases with adhesive thickness. The solid line in the figure represents Dai et al.'s model. A prediction equation is proposed as follows:

\[ G_f = 0.446 \left( \frac{G_a}{t_a} \right)^{0.352} f_c^{0.236} \left( E_f t_f \right)^{0.023} \]

where:
- \( G_f \) = Fracture Energy
- \( b_f \) = Width of CFS

The experimental pull-out strengths are larger than the model predicts. However, the results are similar in terms of shape and rate of increase. In fact, it is found that the difference between 0.2mm and 1mm of adhesive is bigger than the difference between 1mm and 3mm in both experimental results and the prediction. The main reason for this relation between adhesive thickness and pull-out strength is the effect of effective bond length. The effective bond length is the axial distance from the loading end over which the bond stress is borne and it increases with adhesive thickness. A greater effective bond length means that bond stress is carried over a greater length of the CFS and consequently the local bond stress is reduced, making it less likely to reach the local bond strength. The variation in effective bond length will be discussed later in connection with the strain distribution.

The scatter in pull-out strength can be considered a result of variations in concrete strength, concrete surface conditions, errors, and torsion.

The strain distribution over the length of the CFS is shown in Fig. 4. The strains are determined as simple mean values of measured CFS strains at three locations nearby. The strain distribution gradient corresponds to bond stress. That is to say, bond stress is not borne equally over the full CFS. Where the distribution is flat, there is no bond stress. The CFS has already debonded at the load end and the bond stress does not extend that far toward the free end.

In early loading with ST-01, the strain distribution curve forms a parabolic curve and the strain rises gradually. However, the strain stops growing at certain value, which is the local bond strength, and effective bonding extends away from the load end. Finally, effective bonding reaches the free end and the CFS debonds completely from the substrate concrete. This behaviour conforms generally with that clarified in previous research.

Comparing the three specimens with different of adhesive thicknesses in Fig. 4, it is seen that a thicker adhesive layer results in a gentler gradient and greater effective bond length. This verifies the earlier discussion on the increase in pull-out bond strength shown in Fig. 3. Moreover, it can be seen that the growth in effective bond length between 0.2mm and the other adhesive thicknesses (1mm and 3mm) is more obvious. That is to say, effective bond length increases significantly when the adhesive is increased from 0.2mm to 1mm in thickness, but thereafter the increase is smaller. It can be understood that this is reflected in the changes in pull-out bond strength.
FATIGUE TEST

In the fatigue test, adhesive thickness and maximum loading level were set up as experimental parameters. The nine specimens and their fatigue life results are shown in Table 3. The maximum loading level and minimum loading level are based on the ratio of static pull-out bond strength.

<table>
<thead>
<tr>
<th>Properties of specimens and experimental results</th>
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<tbody>
<tr>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>FA-01 0.2</td>
</tr>
<tr>
<td>FA-02 0.2</td>
</tr>
<tr>
<td>FA-03 0.2</td>
</tr>
<tr>
<td>FA-11 1</td>
</tr>
<tr>
<td>FA-12 1</td>
</tr>
<tr>
<td>FA-13 1</td>
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<td>FA-31 3</td>
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<tr>
<td>FA-32 3</td>
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<tr>
<td>FA-33 3</td>
</tr>
</tbody>
</table>

The relation between fatigue life and maximum loading level is shown in Fig. 5. It can be seen that there is a linear relationship between fatigue life and loading level for each adhesive thickness, while fatigue life decreases with adhesive thickness. In contrast with the results for static pull-out bond strength, fatigue life decreases with adhesive thickness for a particular loading level. In particular, the fatigue life for an adhesive thickness of 0.2mm
is much greater than for the other thicknesses. In the case of maximum loading levels from 80% up, the fatigue life exceeds one hundred thousand cycles. On the other hand, the fatigue life for adhesive thicknesses of 1mm and 3mm reaches one hundred thousand cycles when the maximum loading level is 50% or less.

The relation between fatigue life and actual fatigue loading is shown Fig. 6. The curves for adhesive thicknesses of 1mm and 3mm are similar. In the case of fatigue loading of 15kN, fatigue life can reach eight hundred thousand cycles. In the case of an adhesive thickness of 0.2mm, fatigue life barely decreases with maximum loading. With a fatigue loading of 22kN, the specimen with an adhesive thickness of 0.2mm has a slightly longer fatigue life than those with 1mm and 3mm thickness. Consequently the specimens with 0.2mm, 1mm and 3mm thickness show similar fatigue life for loadings around 20kN.

The strain distribution during fatigue testing is shown in Fig. 7. In the same way as in the static test, the strains are calculated as simple mean values of CFS strain given by the strain gauges. These strain distributions are shown for certain numbers of cycles at the maximum load.

Under fatigue loading, effective bond length does not depend on adhesive thickness. In other words, different effective bond lengths during the stages of cyclic loading converge to similar values when fatigue failure is approached. Therefore, due to the similar effective bond length, specimens with adhesive thicknesses of 1mm and 3mm have bond stress higher than static test, and they have a fatigue life shorter than expected. Comparing the three specimen represented in Fig. 7, all of which were under similar loading of around 20-21kN, FA-01 (adhesive thickness of 0.2mm) debonded at the load end after ten of thousands of cycles, whereas FA-12 and FA-33 (adhesive thickness of 1mm and 3mm) reached debonding after only several thousand cycles. That is, specimens with thicker adhesive rapidly debond over the full length of the CFS.

According to these findings, in static loading it is useful to increase the adhesive thickness, but where static and fatigue loading takes place, the thinner adhesive is preferable.
CONCLUDING REMARKS

1. In static loading, pull-out bond strength increases with adhesive thickness. Moreover, the incremental increase in pull-out strength becomes less significant with adhesive thickness.

2. In static loading, pull-out strength increases because of the increase in the effective bond length, which explains the effect of adhesive thickness.

3. Even for extremely thick adhesive, the experimental results correspond with Dai et al.’s model^2\).

4. In fatigue loading, in contrast to the static test, fatigue life decreases with adhesive thickness at a particular loading level.

5. In fatigue loading, in contrast to the static test, specimens with different adhesive thicknesses have the same effective bond length.

REFERENCES


3) Y. Sato: Fatigue Performance of FRP Sheet Externally Bonded to Frost Damaged Concrete, graduation thesis at Hokkaido Univ., 2005