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Interface Slip Control for CFRP-Concrete Composite Beams

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Synopsis: carbon fibre reinforced polymer (CFRP) has been used frequently to retrofit concrete structures. Strengthening efficiency is related to the CFRP application process and the characteristics of the bonding agent. In this paper the mechanism of interface shear behaviour in CFRP to concrete beams is discussed considering previous test observations and mathematical models. This paper then discusses the consequences of introducing interface slip which reduces the integrity of the composite section, however improve ductility and delay debonding failure. The paper suggests that using softer bonding agent as well as setting limits on the interface slip could ensure acceptable serviceability and ductile behaviour.

Keywords: composite materials, carbon fibre polymers, CFRP, retrofitting, interface slip, composite beams, partial interaction.

1. Introduction

Composite sections of various materials are used in engineering applications to fabricate beams, plates and shells and in most cases used for structural strengthening of different sections and materials. The procedure, commonly employed to analyse such systems, is based on the assumption of rigid interconnection between layers. If the layers are fastened together with strong adhesive as in most of laminated plastic as well as welded assemblies, the assumption of rigid interconnection between layers is reasonable. In some widely used system, however, such as in composite steel-concrete beams, the latter assumption is questionable. Furthermore, previous tests (1) have revealed that CFRP composites for structural strengthening are found to develop interface slip during loading. In the analysis of such problems, the interlayer movements, which occur as a result of deformation at the connectors or the bonding material, can significantly affect the overall behaviour.

One of the common techniques available for strengthening reinforced concrete elements is the attachment of external plate i.e. steel plate or CFRP laminate, for which stud shear connectors or bonding agents can be used. For the CFRP composite strengthening system, an externally bonded fibre composites will provide high tensile strength and are utilised for flexural, shear and axial compression confinement of concrete elements. Typical fibre properties are given in Table (1).

Table 1. Common types of fibre (1).

<table>
<thead>
<tr>
<th>Type of fibre</th>
<th>Modulus of elasticity (GPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>240 – 640</td>
<td>2,500 – 4,000</td>
</tr>
<tr>
<td>Aramid</td>
<td>120</td>
<td>3,000 – 4,000</td>
</tr>
<tr>
<td>Glass</td>
<td>65 - 70</td>
<td>1,700 – 3,000</td>
</tr>
<tr>
<td>Polyester</td>
<td>12 - 15</td>
<td>2,000 – 3,000</td>
</tr>
<tr>
<td>Steel</td>
<td>210</td>
<td>550</td>
</tr>
</tbody>
</table>

Controlling the interaction of all components in a composite system is an essential step, and needs to be facilitated so that consistent overall behaviour can be guaranteed. Quantifying the relative movements in the composite system such as the interface slip and separation, in advance and then capping them will enable designers to provide composite sections that comply with serviceability requirements, and hence reduce the risk of excessive deformation.

The CFRP systems have typically been used for beams, slabs and walls for flexure, beams and walls for shear, slabs and walls for trimming around penetrations, silos and tanks for crack control and increased capacity, poles and chimneys for lateral load resistance, marine structures for increased
durability, blast and impact resistance, historic masonry structures to supplement inherent low
strength materials and high ductility against seismic and dynamic stress. The wide range of
applications necessitate the availability of design guide lines to predict the overall behaviour of the
composite elements including interface slip, and hence provide satisfactory sections.

2. Composite action

The connection between the two components of a composite member is an important parameter
which may significantly affect the overall behaviour. Horizontal shear resistance is generally the ruling
criterion for composite beams, and with this in mind, connectors may be classified as either rigid or
flexible. Rigid connectors deform very little under load, while flexible connectors may exhibit
significant deformation. In general a shear connection (adhesive layer) is considered adequate when
failure of the beam is not due to failure of the connection layer (shear or pull-out failure) and the
reduction in the ultimate moment of resistance of the beam, due to slip and separation, is negligible.

There are situations in which stresses tending to cause uplift can occur at the interface. These arise
from complex effects such as the torsional stiffness of reinforced concrete slabs forming flanges of
composite beams, the triaxial stresses in the vicinity of shear connectors and, in box girder bridges,
the torsional stiffness of the steel box. Tension across the interface can also occur in beams of non-
uniform section or with partially completed flanges.

If vertical separation of beams and slabs is to be avoided, the adherent must have adequate
anchoring properties. In practice, empirical design rules are used to ensure adequate anchorage
against vertical separation. Almost all connectors used in practice are therefore so shaped that they
provide resistance to uplift as well as to slip. Uplift forces are so much less than shear forces that it is
not normally necessary to calculate or estimate them for design purposes, provided that connectors
with some uplift resistance are used.

Using externally attached component produces composite section with discontinuity in stress and
strain variations at the interface when applying load. In order to restore discontinuity the selected
bonding agent must be of a strength exceeding the existing interface (longitudinal) shear force. Figure
1(a) compares the variation of bending and shear stresses across a typical composite beam section
for the two extreme cases i.e. full interaction and no interaction. It is worth mentioning that full
interaction is ideal, and depends mainly upon connection density, type, and mechanical properties of
shear connectors.

Previous test observations (2 & 3) showed that composite beams subjected to bending moment will
exhibit differential movement at the interface between components in the form of slip, S, as shown in
Figure 1(b) in which all symbols have their usual meaning. This figure shows that at mid-span, slip
strain is a maximum and slip is zero and, at the end of the beam, slip is a maximum and slip strain is
zero. Through simple elastic analysis of this beam some idea of the magnitude of slip can be given by
relating it to the maximum deflection of the two components of the beam. Usually, end slip is less than
one tenth of the deflection. This shows that shear connection must be very stiff if it is to be effective.
Figure 1. Elastic analysis of composite beam with partial connection (2).
3. Stiffness of shear connectors

The property of a shear connector most relevant to design is the relationship between the shear force transmitted, \( P \), and the slip at the interface, \( S \). This load-slip curve should ideally be found from tests on composite beams, but in practice a simpler specimen is necessary. For the stud connectors, usually used in steel-concrete composite beams, will have the typical load-slip curve, shown in Figure 2(a), and obtained from a standard push-out test, shown in Figure 2(b).

Degree of interaction between composite components can be related directly to the shear stiffness of the connection agent, \( K_s \), which can be defined as the shear force corresponding to unit length of interface slip. \( K_s \) can be calculated as the slope of the tangent to the load-slip curve at the point of acceptable slip. Practically, \( K_s \) can be taken as the secant value of this curve corresponding to a point of 80% from the ultimate shear capacity of the bonding agent.

![Figure 2. Typical test for stud shear connector strength (2).](image)

For the case of Carbon Fibre Composites where single or multi-layered laminates bonded to the tension face of reinforced concrete beam, a uniform bonding agent can be used continuously at the interface having uniform shear stiffness, \( K_s \). Test arrangements, shown in Figure 3 (a), can be used to calculate \( K_s \) for the bonding agent. Figure 3 (b) compares typical load-slip curves obtained from theoretical modelling and test observations for CFRP-concrete epoxy bonding agent (4).
Test arrangements for CFRP bonding agent strength.
(b) Typical load-slip curve for CFRP bonding agent.

**Figure 3. Test for CFRP bonding agent strength (4).**

Considering load-slip curves, shown in Figures 2 & 3, it is evident that the shear connections of any type will exhibit deformation related directly to the interface longitudinal force. Thus introduces partial interaction and strain discontinuity within the cross-section.

4. Test observations

From previous experimental investigations carried out at Monash University, Australia (1, 3, 5-8) and earlier at Cardiff University, UK (9, 10 & 11), the author was able to measure interface slip between the two composite components i.e. between the external CFRP laminates and the concrete surface, and between the concrete slab and steel plate girder in the case of a composite plate girder. Figure 4 shows the load-slip relation traced during the tests on RC beams retrofitted with flexural CFRP sheets alone (test beam RR3) or with coupled flexural-shear CFRP composites (test beams RR4, RR5 and RR6).

**Figure 4. End slip values for tested CFRP retrofitted RC beams (1 & 5).**
Test results, given in Table 2, indicated an increase of 17% in shear strength and an average increase of 95% in flexural strength, in comparison with control test beam RR1 when retrofitted with CFRP and allowing for interface slip. Furthermore, the load-deflection curves for these beams, shown in Figure 5, indicate a reasonably ductile behaviour.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Concrete concrete compressive strength (MPa)</th>
<th>Total failure load (kN)</th>
<th>Applied shear (kN)</th>
<th>Applied moment, (kN.m)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR1*</td>
<td>37.8</td>
<td>106.19</td>
<td>53.10</td>
<td>37.17</td>
<td>Shear</td>
</tr>
<tr>
<td>RR2</td>
<td>39.47</td>
<td>121.40</td>
<td>60.70</td>
<td>42.49</td>
<td>Flexure</td>
</tr>
<tr>
<td>RR3</td>
<td>39.06</td>
<td>100.30</td>
<td>50.15</td>
<td>60.18</td>
<td>Shear</td>
</tr>
<tr>
<td>RR4</td>
<td>39.43</td>
<td>112.08</td>
<td>56.04</td>
<td>67.25</td>
<td>Flexure (CFRP break)</td>
</tr>
<tr>
<td>RR5</td>
<td>38.97</td>
<td>123.18</td>
<td>61.59</td>
<td>73.91</td>
<td>Flexure (CFRP break)</td>
</tr>
<tr>
<td>RR6</td>
<td>40.95</td>
<td>126.32</td>
<td>63.16</td>
<td>75.79</td>
<td>Flexure (CFRP break)</td>
</tr>
</tbody>
</table>

* Control beam (concrete beam without CFRP)
** Cylinder tests at the same age of the main beam

Figure 5. Load-deflection curves for test beams RR3-RR6 (1 & 5).

5. Mathematical modelling for partial interaction behaviour

Most previous mathematical modelling for the composite sections assumed full interaction at the interface based on a rigid connection condition. In other words, composite components joined together by an infinitely stiff shear connection where slip and slip strain are everywhere zero. This is difficult to achieve and misrepresents the actual behaviour.

Mathematical models had been developed by the author to predict the partial interaction behaviour of steel-concrete composite beams and multi layered CFRP retrofitted RC beams (3, 6, 8 & 10) allowing for inter-laminar slip. Basic assumptions include linear material properties, continuous shear connection, non-flexural CFRP element capable of sustaining axial force only, The amount of slip permitted by the bonding agent is directly proportional to the load transmitted between layers at any given load on the beam, and each layer deflects the same amount (no separation between layers).

The basic equilibrium and compatibility equations were expressed in terms of displacement variables and combined to give a set of higher order differential equations. The resulting differential equations can be solved numerically by expressing the displacement derivatives in finite difference form and satisfying the boundary conditions at supports.
Figure 6 shows the assumed composite element used to represent the multi layered CFRP retrofitted RC beams with partial interaction. It consists of a layer of concrete with a length of \((\delta_x)\) and having \((n)\) layers of CFRP attached to its tension face. The composite element is subjected to bending moment \((M_c)\), shear force \((V_c)\) and axial forces \((F_C), (F_1), \ldots, (F_n)\). Subscripts \((c)\) denote concrete and \((1 – n)\) denote CFRP layers. The \(x\)-\(z\) coordinate system is passing through the centroid of the concrete component of the composite element.

The final set of differential equations for the case of \((n)\) layers of CFRP are given below, in which \(x\) denotes differentiation, \(W\) & \(U\) are the displacements for the concrete and CFRP elements, \(d\) denotes the distance between the CFRP layer and the centre of axes, \(E, I\) & \(A\) are the modulus of elasticity, second moment of area and sectional area of the two materials respectively. The mathematical model was verified through applications to a wide range of previous tests in literature and gave close agreement with results.

\[
Ec.Ac.W,xxx - E_1.A_1.U_1,xxx.d_1 - E_2.A_2.U_2,xxx.(d_1 + d_2) - E_3.A_3.U_3,xxx.(d_1 + d_2 + d_3) - \ldots - En.An.Un,xxx.(d_1 + d_2 + \ldots + dn) = \rho \tag{1}
\]

\[
\]

\[
Ec.Ac.Uc,xx + Ec.Ac.(Ec - Ec) - Ks_1.([Uc - Zci.Wc, x] - U_1) = 0 \tag{3}
\]

\[
Ec.Ac.Uc,xx + Ec.Ac.(Ec - Ec) + E_1.A_1.U_1,xx - Ks_2.(U_1 - U_2) = 0 \tag{4}
\]

\[
Ec.Ac.Uc,xx + Ec.Ac.(Ec - Ec) - Ks_1.([Uc - Zci.Wc, x] - U_1) = 0 \tag{5}
\]

Up to CFRP layer number \((n-1)\) which has the following equation:

\[
Ec.Ac.Uc,xx + Ec.Ac.(Ec - Ec) + E_1.A_1.U_1,xx + E_2.A_2.U_2,xx + \ldots + E.(n-2).A.(n-2),U.(n-2),xx - Ks.(n-1).([U.(n-2) - U.(n-1)] = 0 \tag{5}
\]

While for the last CFRP layer number \((n)\), the differential equation is:

\[
En.An.Un,xx + Ks.(U.(n-1) - Un) = 0 \tag{6}
\]
6. Controlling interface slip

Except in design with partial shear connection, all design of composite beams and columns in practice is based on the assumption that full interaction is achieved. In this respect, using rigid bonding agent reduces the value of the interface slip, which approaches zero for infinitely stiff shear connection. In this case, a premature failure will be expected and will disadvantage the retrofitting mechanism and the feasibility of composite action. Therefore, accepting the presence of a reasonable interface slip accompanied with improved ductility seems to be logical.

Using rigid bonding agent attracts high stresses at the interface region. The weakest of the three composite components i.e. the hosting material, the external plate and the bonding agent, will experience excessive stresses leading to early failure. For the case of CFRP-concrete composite section, the concrete element will be the weakest and the first to fail, and as most previous test observations have reported, premature failure is typically characterised by debonding of the CFRP laminates with ripping off the bonded concrete cover (12 & 13).
Having facilitated the prediction of interface slip at the CFRP-concrete composite beam and defining the load-slip relation for the bonding agent, a reasonable limit can be introduced for the interface slip and the subsequent longitudinal shear force transferred between layers. This limit can be selected so that acceptable serviceability behaviour is ensured with a consistent behaviour of all composite components.

In order to further improve the composite behaviour, a relatively soft bonding agent is recommended with low shear stiffness value. Larger interface slip will be expected with improved ductile behaviour, and hence delayed failure.

7. Conclusions

From the above discussion and previous test observations and mathematical modelling, the following recommendations and conclusions can be introduced:

1. If external plates and laminates are used to retrofit reinforced concrete beams, it is advisable to choose a relatively soft bonding agent, which will delay failure and enhancing ductility.

2. Using a rigid bonding agent will introduce premature failure and debonding of the external laminates with ripping off the concrete cover due to stress concentration at the interface.

3. Full composite behaviour can not be guaranteed by using a rigid connection in which case the integrity of the composite components may be lost at earlier loading stages, depending on what the concrete interface shear strength is.

4. It is recommended to accept a relatively large interface slip value provided that acceptable serviceability behaviour will be ensured.

5. Interface slip values should be capped at a limit introduced so that consistent behaviour of the composite section can be guaranteed.

8. References


