Experimental Study on the Bond-Slip Behaviour of CFRP Laminate Bonded on RC Tension Members

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ABSTRACT: A series of 8 reinforced concrete (RC) tension members retrofitted with CFRP laminates were recently tested at ETH Zurich in order to study the bond behaviour of carbon fibre reinforced polymer (CFRP) laminates glued on concrete. Different specimen configurations, varying the reinforcement ratio of conventional reinforcement and CFRP laminate, were investigated, using a conventional as well as a novel, recently developed adhesive. High resolution 3D digital image correlation measurements allowed for actually measuring the bond-slip and bond-separation behaviour of bonded CFRP laminates and scrutinizing the concrete cracking at and near the laminate-concrete interface.

In comparison with current (design) provisions, e.g. by Zilch et al. (2012) and SIA 166 (2004), the measured fracture energy, especially of the recently developed adhesive, appears to be considerably higher, mainly due to higher peak bond stresses and higher corresponding slips. The measured elastic slope, however, corresponds well with the values found in the pertinent literature.

1 INTRODUCTION

Externally bonded carbon fibre reinforced polymer (CFRP) laminates have already been used worldwide to strengthen load carrying reinforced concrete (RC) members in buildings and different types of bridges. The available knowledge has consequently increased and, together with results from experimental research, led to the establishment of design guidelines in several countries.

Bond between concrete and reinforcement is one of the most important aspects of structural concrete behaviour and key to the understanding of phenomena like tension stiffening, rotation capacity, anchorage length, and crack formation. The bond behaviour of CFRP laminates bonded on concrete mainly depends on the used adhesive, the quality of the concrete surface, the concrete properties, and the cracking behaviour of the RC member. In the pertinent literature, a bilinear bond-slip model (with $\tau_{bl}$ as peak bond strength, $s_{bl}$ as slip at peak bond stress, and $s_{fl}$ as maximum slip) is typically used as a constitutive law for solving the differential equation describing the bond behaviour of a tension chord reinforced by externally bonded FRP (e.g. Neubauer (2000), Ulaga (2003), CNR-DT200 (2004), SIA 166 (2004), Czaderski (2012), Zilch et al. (2012)). Several empirical relationships are given by the above named authors and
Institutions for determining the characteristic values of the bilinear bond-slip law. Table 1 shows the values postulated by Zilch et al. (2012) (DAfStb Report No. 592) and SIA 166 (2004).

Table 1. Parameters for bilinear bond-slip relationship ($d_{max}$ - maximum concrete grain size)

<table>
<thead>
<tr>
<th></th>
<th>$\tau_{bf0}$</th>
<th>$s_{f0}$</th>
<th>$s_{f1}$</th>
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<tbody>
<tr>
<td>Zilch et al. (2012)</td>
<td>$0.366\sqrt{\alpha_c f_{cm} \alpha_t f_{ct}}$</td>
<td>$2.5 \frac{2.5 \text{ mm} + 3d_{max}}{E_c} \tau_{bf0}$</td>
<td>0.201 mm</td>
</tr>
<tr>
<td>SIA 166 (2004)</td>
<td>$\frac{4}{3} f_{ct}$</td>
<td>$-\frac{2G_{lc}}{\tau_{bf0}}$</td>
<td>0.1875 mm</td>
</tr>
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While the aforementioned approaches provide similar values for the fracture energy (area below bond-slip curve), there are substantial differences for the slip $s_{f0}$ at peak bond stress. This results in a considerable uncertainty on the fatigue resistance which is highly dependent on the bond stiffness, as recently observed by Ambrasas (2015) and Budelmann and Leusmann (2012).

In order to fully understand the response of tension members and validate bond models, accurate measurements of the strains on CFRP laminates and slips between the laminates and the concrete surface are fundamental. However, current state-of-art strain measuring instrumentation (such as strain gauges attached to the laminates) are only possible at discrete locations. Digital Image Correlation (DIC) is an optical instrumentation technique that permits to measure full-field displacements and calculate strains over the entire surface of a tested specimen without affecting its response, hence circumventing the limitations of traditional instrumentation. At the Institute of Structural Engineering (IBK) of ETH Zurich, DIC has recently been used for several applications (e.g. see Haefliger et al. (2017)).

Eight reinforced concrete (RC) tension members retrofitted with CFRP laminates were recently tested at ETH (Lötscher (2016) and Gomer (2017)) using high resolution DIC measurements in order to explore its potential.

2 TEST SETUP

2.1 Materials

2.1.1 Concrete

All specimens were cast on 11 March 2016. Specimens CFK1 to CFK4 were tested between 12 April and 4 May (age 32 days to 54 days) whereas Specimens CFK5 to CFK8 were tested between 2 November and 16 December (age 236 days to 280 days). The concrete properties (mean cylinder strength $f_{cm}$, mean cube strength $f_{cm,cube}$, mean Young’s modulus $E_{cm}$, indirect tensile strength $f_{ctm}$, and pull-off strength $f_{ctl}$) were determined from materials tests at ETH Zurich and are given in Table 2 in correspondence to the relevant specimens.

2.1.2 Reinforcement steel

The used reinforcing bars ($\varnothing$14 mm, without distinct yield plateau and $\varnothing$20 mm, with yield plateau) were tested at ETH Zurich. The $\varnothing$14 mm reinforcing bar exhibited a static yield strength $f_{s,stat} = 524$ MPa and a static tensile strength of $f_{t,stat} = 573$ MPa. The $\varnothing$20 mm reinforcing bar had
a static yield strength \( f_{s,stat} = 510 \text{ MPa} \) and a static tensile strength of \( f_{t,stat} = 595 \text{ MPa} \). The Young’s modulus was 193 GPa (\( \varnothing 14 \text{ mm} \)) and 195 GPa (\( \varnothing 20 \text{ mm} \)), respectively.

### 2.1.3 CFRP laminate

Laminates with 50 mm width and 1.2 mm thickness were used in the tests (manufacturer information: mean static tensile strength \( f_{lm} = 3100 \text{ MPa} \), mean Young’s modulus \( E_{lm} = 170 \text{ GPa} \)).

### 2.1.4 Adhesive

Two different adhesives were used: a standard adhesive and a recently developed, new adhesive. The thickness of the adhesive layer was approximately 1 mm. The mean Young’s moduli (manufacturer information) were \( E_{a,standard} = 10 \text{ GPa} \) and \( E_{a,new} = 4.0 \text{ GPa} \), corresponding to shear moduli of \( G_{a,standard} = 4.65 \text{ GPa} \) and \( G_{a,new} = 1.79 \text{ GPa} \) when assuming a Poisson ratio of 0.3.

### 2.2 Test specimens

A series of 8 reinforced tension members with a length of 1.4 m and cross-sectional dimensions of 150 mm x 150 mm were tested. Test parameters included the diameter of the reinforcing bar (14 mm or 20 mm), the type of adhesive (standard or new adhesive), and the configuration of the CFRP laminates (see Table 2). Specimens CFK1 to CFK4 were tested with 4 laminates (two on front and back) while CFK5 to CFK8 were tested with 2 laminates (one on front and back). The front/side view as well as the cross section of selected specimens are shown in Figure 1 and Figure 2.

![Figure 1](image1.png)

**Figure 1.** Specimen in side view (top); Specimens CFK1 to CFK4 (middle) and CFK5 to CFK8 (bottom) in front view.

### 2.3 Measurements

The global force and displacement were measured by the testing machine’s built-in load cell and displacement sensor, respectively. The measurement system of main interest for this paper was digital image correlation (DIC). In addition, strain gauges (SG) were applied to the specimens for controlling reasons during the test and validation of DIC.
Table 2. Configurations of the 8 tested specimens

<table>
<thead>
<tr>
<th></th>
<th>CFK1</th>
<th>CFK2</th>
<th>CFK3</th>
<th>CFK4</th>
<th>CFK5</th>
<th>CFK6</th>
<th>CFK7</th>
<th>CFK8</th>
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<tbody>
<tr>
<td>Reinf. bar Ø20mm</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Reinf. bar Ø14mm</td>
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<td></td>
<td>x</td>
<td></td>
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<td>x</td>
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<tr>
<td>Standard adhesive</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>New adhesive</td>
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<tr>
<td>Concrete properties (in brackets: number of tests)</td>
<td>$f_{cm} = 38.2$ MPa (3), $f_{cm, cube} = 39.1$ MPa (2), $f_{cm} = 2.9\pm3.7$ MPa (2+1), $f_{ctm} = 2.5$ MPa (4)</td>
<td>$f_{cm} = 46.4$ MPa (3), $f_{cm, cube} = 55.5$ MPa (2), $E_{cm} = 29.1$ GPa (3), $f_{cm} = 3.6$ MPa (3), $f_{ctt} = 2.3\pm3.5$ MPa (3x4)</td>
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Figure 2. Cross-section of specimens CFK1 to CFK4 (left) and CFK5 to CFK8.

DIC is an optical instrumentation technique that allows measuring full-field displacements on a speckled surface without contact to the specimen. By setting two cameras pointing at a surface in different angles, 3D-displacements can be captured. These full-field displacements can then be used to calculate quasi-continuously full-field strains with an uncertainty depending on several parameters such as camera resolution, lenses, camera distance, speckle pattern, as well as careful handling including calibration. The uncertainty was assessed with a zero strain movement of the specimen before the actual test was started, in which all the observed strains and relative displacements can be considered to be due to the uncertainty of the measurement.

Two types of cameras were used in this experimental campaign capturing deformations from the front and the back, but only the results of measurements with the camera “Allied Vision Prosilica GT6600” (referred to as Prosilica in the following, resolution: 6’576 x 4’384 px) are used in this paper. The DIC configuration with the Prosilica cameras was changed several times throughout the test series: Specimens CFK1 to CFK4 were monitored from the front capturing a field of 150 mm x 700 mm on the specimen surface and Specimens CFK5 to CFK8 from the back capturing a field of 150 mm x 250 mm on the specimen surface. In Figure 3, a schematic side view of the test specimen in the testing machine Schenck 1600 kN with the tested DIC-configurations using the Prosilica is shown. Measurements were taken at an interval of 1 Hz.
The strain field was computed from the displacement field considering a virtual gauge length of 28 mm (Specimens CFK1 to CFK4) and 3.5 mm (Specimens CFK5, CFK7, and CFK8), respectively. Given this virtual gauge length, the zero strain movement exhibited the uncertainty noted in Figure 3. The uncertainty is defined here as twice the standard deviation ($\mu \pm 2\sigma$ covers 95.4% of the measurements). The comparison with SG-measurements showed deviations lying within the measured DIC strain uncertainty, which validates the measurement uncertainties. The DIC measurements of specimen CFK6 were considerably less accurate due to technical problems during the test and are not used.

Bond stress between CFRP laminate and concrete at any position in the longitudinal direction of the specimen were calculated depending on the slope of the strain-space curve of the laminate, assuming the Young’s modulus given by the CFRP provider. Virtual points on the concrete and the laminate as close as possible to the edges of the CFRP laminate were chosen to analyse the strain and the corresponding slip. For calculating the slip (i.e. the difference between the displacements on either side of laminate and concrete), the horizontal distance of considered virtual points at the edge of the CFRP laminate and concrete on the specimen surface was 25 mm for specimens CFK1 to CFK4 and 7 mm to 10 mm for CFK5 to CFK8 (15 mm for one laminate of CFK8).

2.4 Loading

The tension tests were conducted with the testing machine Schenck 1600 kN at ETH Zurich. The load was applied to the reinforcing bar and the CFRP laminates through stiff steel “heads” (see Figure 3). Threads were provided at the ends of the reinforcing bars in order to bolt them to the heads. The CFRP laminates were anchored in the heads by means of two clamped, grid-blasted steel surfaces over a length of 155 mm.

The specimens were monotonically loaded in axial (i.e. longitudinal) tension until failure. The loading was displacement-controlled, with a rate of 0.12 mm/min until complete debonding of the laminates occurred. Subsequently, the rate was increased to 0.6 mm/min until failure.
3 TEST RESULTS

For specimens CFK1 to CFK4, the DIC measurements of several tension chord elements (i.e. elements between two neighbouring cracks, varying number due to limited measurement accuracy for detecting fine cracking) on two laminates were analysed at several time intervals:

- CFK1: 12 values on 6 half tension chord elements (TCE) for \( \tau_{0\text{bf}} \) and \( s_{\text{bf}} \), 0 TCE for \( s_{\text{lf}} \)
- CFK2: 12 values on 6 half TCE for \( t_{0\text{bf}} \) and \( s_{\text{bf}} \), 4 values on 2 half TCE for \( s_{\text{lf}} \)
- CFK3: 8 values on 4 half TCE for \( t_{0\text{bf}} \) and \( s_{\text{bf}} \), 4 values on 2 half TCE for \( s_{\text{lf}} \)
- CFK4: 20 values on 10 half TCE for \( t_{0\text{bf}} \) and \( s_{\text{bf}} \), 4 values on 4 half TCE for \( s_{\text{lf}} \)

The slip at peak bond stress \( s_{\text{bf}} \) was determined as the maximum slip difference between the point of zero bond stress and the point of maximum bond stress. The maximum slip \( s_{\text{lf}} \) at delamination was defined when the CFRP laminate was separated from the concrete. As long as bond is intact, the separation is accumulating from the crack to the middle of the TCE (i.e. there are two slopes towards the middle of the TCE). The moment when the separation slope over the length of the TCE does not change direction anymore is interpreted as the moment of delamination.

In the case of specimens CFK5, CFK7, and CFK8 a more detailed analysis of the DIC measurements was possible due to the higher spatial measurement resolution, but reducing the field of view to one TCE at most (usually one complete half). In Figure 4 (left), a series of bond-slip curves are shown, originating from 50 points over a length of 50 mm at the laminate edge after applying to the direct DIC outputs several time filters and four subsequent space filters of 5 mm length. By using the filters, the measurement uncertainty is improved considerably at the cost of reducing the spatial resolution: the original virtual gauge length of 3.5 mm is increased, to approximately 11 mm. The bond stresses after delamination (being zero in reality) were calculated in order to the actual uncertainty in the measurement of the local bond. This uncertainty was \( \pm 5.4 \) MPa (twice the standard deviation) for test CFK5, \( \pm 10.3 \) MPa for CFK7, and \( \pm 9.7 \) MPa for CFK8. This value corresponds to a strain variation of 0.05\% over 2 mm length, well below the strain uncertainty originally provided by the virtual gauge length of 3.5 mm (\( 2\sigma_{\varepsilon} = 0.14\% \) to 0.18\% for CFK5-CFK8, see section 2.3), as can be seen in the following expression:

\[
\Delta\varepsilon_i \approx \frac{\tau_{0\text{bf}} \cdot \Delta x}{E_i \cdot t_i} = \frac{5.4 \text{ MPa} \cdot 2 \text{ mm}}{170 \text{ GPa} \cdot 1.2 \text{ mm}} = 0.05\%
\]

Studying the strains of one laminate and the adjacent concrete, respectively, over the whole captured length at a defined time step between concrete cracking and steel yielding, extensive fine cracking, especially in the region of the main crack, is clearly observed (see Figure 4, right). It is identified by (i) highly localised concrete strains and (ii) the stepped curve of laminate strains (horizontal steps in laminate strain curve). This extensive cracking increases with the applied load. The presence of this series of cracks leads to numerous local strain concentrations, which cannot be tracked with the used DIC instrumentation.

As expected, maximum bond stresses occur at the locations with the highest strain variation, see Figure 4 (right). By averaging the measured bond stress over the element length, the uncertainty in bond stresses discussed above can be further improved. Hence, as an example, four positions were manually selected. The bond stress was then evaluated by applying a mean space filter to smooth the results (corresponding to a virtual strain gauge of around 20 mm base length, see hatched area for Specimen CFK5 in Figure 4, right), resulting in the twice 4 bond-slip curves for both laminate edges (thin lines) shown in Figure 5 (top left for CFK5). Taking the average of these 8 curves at defined slip values, the average bond-slip curve plotted (bold line). This type of evaluation was carried out for CFK7 and CFK8 as well, see Figure 5 (bottom). The computed and measured peak values \( \tau_{0\text{bf}} \), \( \xi_{\text{bf}} \), and \( s_{\text{lf}} \) of Specimens CFK1 to CFK4 are also shown. The variation
coefficients of the given mean peak values obtained from several TCE of Specimens CFK1 to CFK4 were: $\nu_{bf0} = 27\%$, $\nu_{sf0} = 53\%$, and $\nu_{sf1} = 30\%$.

Figure 4. Analysis of the captured surface length of specimen CFK5, Laminate 1. Left: bond-slip-curves of a space interval of 50 mm (570 mm to 620 mm, one curve per 1 mm) within a tension chord element over time; right: laminate/concrete strain and bond stress over the captured surface length at one time step between concrete cracking and steel yielding

Figure 5. Bond-slip curves for CFK2/CFK5 (top left), CFK3/CFK8 (bottom left), and CFK4/CFK7 (bottom right) measured by means of DIC

Generally, the fracture energy appears to be lower when using the standard adhesive than when using the recently developed, new adhesive. The ascending branch (elastic bond) and a descending branch (deterioration of the bond) can clearly be identified due to a very low uncertainty in deformations (see section 2.3). In comparison with current (design) provisions given in Figure 5 (Zilch et al. (2012) (DAfStb) and SIA 166 (2004)), the measured fracture energy appears to be considerably higher, mainly due to higher peak bond stresses and higher corresponding slips (two curves are given to account for minimum and maximum concrete tensile
strengths throughout the test series). The elastic slope given by Zilch et al. (2012), however, corresponds well with the measured results.

4 CONCLUSIONS

A series of 8 reinforced concrete (RC) tension members retrofitted with CFRP laminates were recently tested at ETH Zurich in order to study the bond behaviour of carbon fibre reinforced polymer (CFRP) laminates glued on concrete. Different specimen configurations, varying the reinforcement ratio of conventional reinforcement and CFRP laminate, were investigated, using a conventional as well as a novel, recently developed adhesive. High resolution 3D digital image correlation measurements allowed for actually measuring the bond-slip and bond-separation behaviour of bonded CFRP laminates and scrutinizing the concrete cracking at and near the laminate-concrete interface. In comparison with current (design) provisions, e.g. by Zilch et al. (2012) and SIA 166 (2004), the measured fracture energy, especially of the newly developed adhesive, appears to be considerably higher, mainly due to higher peak bond stresses and higher corresponding slips. The measured elastic slope, however, corresponds well with the values found in the pertinent literature.

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REFERENCES


