Flexural strengthening of beams using externally bonded plates: advanced optical measurements at the beam-to-plate interface

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Summary
In a first test series, small-scale steel beams reinforced with adhesively bonded carbon fibre reinforced polymer (CFRP) plates were subjected to four-point bending. Phase-stepping 3D-digital speckle pattern interferometry (DSPI) was employed to measure the strain concentrations near the end of the CFRP plate, with a special focus on shear and normal strains. Furthermore, a refined finite element analyses (FEA) of the strengthened beam was carried out to predict these strains. Comparisons between measured and calculated strains have confirmed a strong variation of shear strain across the adhesive layer. The FEA has also shown the much higher normal strains present at the adhesive-steel (AS) interface than at the plate-adhesive (PA) interface. This difference has been suggested as the reason why debonding failure more commonly occurs at the AS interface rather than the PA interface. In a second study using optical measurement capabilities, a reinforced concrete (RC) beam was strengthened in flexure using a CFRP plate and tested in a four point bending test. In this study both conventional measurement techniques as well as an optical 3D image correlation system (ICS) were used to measure the displacements at the tension face of the beam. Results from the ICS measurements have shown interesting and unexpected slip distributions, in particular at the CFRP plate ends. Further experimental and analytical study is needed to confirm and understand this behaviour.

Keywords: External bonding, flexural strengthening, digital speckle pattern interferometry (DSPI), 3D image correlation system.

1. Introduction
Several advantages, from economical to practical, exist in the application of externally bonded steel or composite plates to steel-reinforced concrete beams for the purpose of flexural strengthening. In order for this technique to be effective, however, a thorough understanding of the connection between the beam and the plate is required. Numerous experimental studies over the past two decades have reported on the failure modes that can be expected for externally bonded reinforced concrete beams, including the commonly seen plate end debonding as well as intermediate crack induced interfacial debonding. Analytical and numerical models have been developed, for example, for plate end debonding [1], [2], [3], that allow for the prediction of the local interfacial shear and normal stress concentrations that lead to debonding failures. Another significant parameter in the debonding process is the slip, that is, the relative displacement between the plate and the concrete surface. It is known that when the slip reaches a certain value, no more shear stress can be transferred and debonding occurs. Bond shear stress –slip relationships for FRP plates adhesively bonded to concrete can be found in the literature [4], [5].

The experimental verification of the analytical and numerical models, as well as the measurement of the slip, however, has been difficult. This is mainly due to the scant amount of information that is obtained using standard measuring techniques, e.g. electrical and mechanical strain gauges, where a
limited number of discrete measurement points are distributed along the length of the beam. For this reason, two recent test series have employed non-contact, full-field optical measurement methods in order to produce a more complete picture of the displacement fields in the areas of interest such as in the vicinity of cracks and at the carbon fibre reinforced polymer (CFRP) plate end.

Non-contact optical methods are increasingly being used as verification for FEA results in mechanical, optical and civil engineering. Both moiré interferometry and speckle methods have been used, e.g. to detect crack initiation from strain profiles in fibre-reinforced composites, to assess strain in composite lap-joints or to measure the strain concentration close to the weld toe of a tubular steel joint.

In the first part of the paper, measurements on a small-scale CFRP reinforced steel beam using digital speckle pattern interferometry (DSPI) are made (Fig. 1). DSPI is well suited for strain analysis at the plate end due to its high sensitivity. For the first time, a comparison of optically measured values to the values of shear and normal strain at the plate end obtained using a FE analysis are made. In a second part of the paper, measurements along the length of a CFRP plate using an optical 3D image correlation system (ICS) are presented. The relative displacement (slip) between the CFRP plate and the concrete surface will be determined and give interesting information about the bond behaviour of the CFRP plate.

2. **DSPI measurements and FEA of small-scale CFRP reinforced steel beams**

   2.1 **Experiment**

Two 1.0 m long I-section steel beams were strengthened in flexure using two adjacently placed CFRP plates (Fig. 1). Steel beams were used instead of the more commonly tested CFRP strengthened concrete beam in order to preclude cracking, and since steel, with its smoother surface, more often results in better optical measurement results. The properties of the CFRP plates, adhesive and steel beam are given in Table 1. The two steel beams were identical except for the plate and adhesive thicknesses. The beams were loaded with manually controlled hydraulic jacks in a four-point bending arrangement installed on a vibration isolated optical table (Fig. 2, left). The loads were distributed to the beams through two 120 mm long steel plates; the beams were supported by 90 mm long plates. For control purposes, standard electrical resistance strain gauges were applied to the top flange of the steel beams and CFRP plates at mid-span. Deflection of the beams at mid-span was also measured using a mechanical dial gauge.

![Fig. 1: Simply supported test beam subjected to four-point bending, in mm](image)

The measurement of deformations at the end of the adhesively bonded CFRP plate where strain concentrations were expected was carried out using a 3D digital speckle pattern interferometry (DSPI) system. Speckle interferometric techniques rely on laser light to illuminate a rough surface. The diffusively back-scattered light appears in a noisy and spotted pattern called speckle pattern. Depending on the optical configuration used, this speckle pattern modifies in relation to the local displacement undergone by the surface. The interferometric system detects the optical path difference due to the local displacement and displays it in the form of fringe maps.
Table 1: Linear-elastic material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$</th>
<th>$v$</th>
<th>$t$</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>205000 MPa</td>
<td>0.3</td>
<td>0.76 mm$^2$</td>
<td>0.60 mm$^2$</td>
</tr>
<tr>
<td>Adhesive (Sikadur-30$^®$)</td>
<td>12800 MPa</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CFRP plate (Sika CarboDur$^®$)</td>
<td>174000 MPa</td>
<td>0.28</td>
<td>1.37 mm$^2$</td>
<td>2.30 mm$^2$</td>
</tr>
</tbody>
</table>

1. Given by manufacturer
2. Measured values

Figure 2 (right) shows the measurement area of approximately 16 x 11 mm$^2$ at plate end. The area was illuminated with a Nd:YVO-laser (wavelength, $\lambda = 532$ nm) sequentially from three directions. At each load level, DSPI phase maps for the three illumination directions were taken with OPTOCAT Software (Breuckmann). A standard four-frame phase-stepping algorithm was applied. The phase maps were transformed to Cartesian displacement components ($u$, $v$, $w$) using the appropriate transformation matrix that was calculated from the geometry of the experimental set-up. This resulted in a sensitivity of 0.299 $\mu$m/fringe in-plane ($u$ and $v$ components) and 0.183 $\mu$m/fringe out-of-plane ($w$ component).

2.2 FE modelling of plate-end strains

A 3D linear-elastic finite element analysis of the strengthened beam was conducted using the commercial finite element code ABAQUS$®$. The element C3D20R—a three dimensional, 20-node quadratic brick element with a reduced integration scheme and six degrees of freedom at the nodes—was used to model the beam specimen.

In order to model precisely the plate end, a submodelling procedure was carried out. Submodelling is the study of a local part of a model based on an existing solution from a global model. That is, a global solution is obtained using a coarse mesh, interpolated onto the boundary of a locally refined mesh, resulting in a detailed solution in the local area of interest. To avoid numerical problems, the submodelling was divided into two steps. In the first step, a semi-refined submodel, Submodel 1, was created. Submodel 1 was driven by solutions from the Coarse model. A second, even more refined submodel, Submodel 2, was then created. Submodel 2 was driven by solutions from Submodel 1. Figure 3 shows the coarse and submodels used in the FE analysis. Also shown in Fig. 3 are the kinematic boundary conditions required to simulate the planes of symmetry of the quarter-beam model.

The material properties of the adhesive and steel are presented in Table 1 above; for the CFRP the following orthotropic material properties were implemented in the analysis (the orientation of the
axes is shown in Fig. 3): $E_1=9000$ MPa, $E_2=9000$ MPa, $E_3=174000$ MPa, $G_{13}=2000$ MPa, $G_{23}=4500$ MPa, $G_{12}=44000$ MPa, $\nu_{13}=0.04$, $\nu_{23}=0.28$, $\nu_{12}=0.28$. A convergence study was carried out, whereby further refinement of the element mesh (to the mesh that is shown in Fig. 3, Submodel 2) resulted mainly in an increase in strain at points of singularity, e.g. plate end, steel-adhesive interface. The Submodel 2 mesh presented here includes elements widths of 0.1 mm at the plate end and element heights of 0.06 mm at the plate-adhesive-steel beam interfaces.

### 2.3 Results

For quantitative strain analyses and comparison purposes, the optically measured in-plane displacement data were filtered and numerically differentiated. Different fitting strategies were used to average out the noise, including a set of cubic splines within intervals along each line. The polynomial coefficients of the splines were calculated according to a least squares criterion under the boundary condition of continuity of the first and second derivatives of the resulting fit line at the interval borders. The strain values were then calculated numerically from the fit lines. Figure 4 shows the normal and shear strain maps, $e_22$ and $e_23$, in $\mu$m/m at plate end, at a load, $P$, of 40 kN. Only the results from Beam 2 are presented here. On the right in Fig. 4 the shear strain clearly reaches a maximum in the adhesive layer near the plate end. For the normal strain, there seems to be no distinct maximum in the strain field. However it might be drowned in the relatively high noise level or it is highly concentrated. The uncertainty in the strain values from the DSPI evaluation is estimated from the standard deviation over a range of constant strain values. It is found to be approximately 100 $\mu$m/m for values obtained from the noisier y-displacement field (see Fig. 2 for coordinate system), and approximately 40 $\mu$m/m for values obtained from the x-displacement field.

![Fig. 3: 3D FE model, coarse and submodels (Beam 2)](image)

Figure 5 presents the normal and shear interfacial strains obtained from FE Submodel 2. The results in Fig. 5 are shown for a load, $P$, of 40 kN and are taken along the paths shown in Fig. 3. The results are very similar to 2D FEA results presented by [6]. On the left in Fig. 5 the normal strains along Paths 1 and 3 diverge at a distance very close to the plate end, whereby the normal strain at the adhesive-steel (AS) interface (Path 1) is considerably higher than the strain at the plate-adhesive (PA) interface (Path 3). This difference has been suggested by others as the reason why debonding failure almost always occurs at the AS interface rather than the PA interface [7]. As expected, the
shear strains on the right in Fig. 5 tend to zero at plate end; the peak shear strain occurs very close to the plate end (approx. 0.5 mm from the plate end along Path 2), which is due to the thin adhesive layer (0.60 mm). [6] found in their FEA study that the distance at which the shear peak occurs from the plate end reduces with a reduction in the adhesive layer.

Fig. 4: Optical measurement results. Normal (left) and shear (right) strain maps close to plate end, in μm/m

Fig. 5: FEA results. a) Normal and b) shear strains close to plate end. ◆ Path 1 (AS), ■ Path 2 (MA), ○ Path 3 (PA)

Figure 6 presents the normal and shear strains obtained from Submodel 2 and the shear strains from the optical measurements across the through-thickness of the adhesive (from the plate-adhesive interface to the steel-adhesive interface) and at different distances from the plate end. It is believed that this is the first comparison of numerically obtained plate end strains with measured values ever made. The variation in normal strain across the adhesive confirms the observation from above: the normal strain near plate end is much higher at the AS interface (Path 1) than at the PA interface (Path 3). In Fig. 6 (right), a good agreement is seen between measured and FEA results. A comparison between calculated and measured normal strains could not be made for this round of measurements, due to the high level of noise in the y-direction (as explained above); further tests are planned. The measured results confirm that the shear strain varies strongly across the adhesive layer near the plate end. This variation is less pronounced farther away from the plate end (see e23 curve at 0.439 mm from plate end).

3. 3D image correlation measurements on a CFRP plated RC beams

3.1 Experiment

In a second study using optical measurement capabilities, a reinforced concrete (RC) beam was strengthened in flexure using a CFRP plate and tested in a four point bending test. The beam and test set-up are shown in Fig. 7.
The materials used for the tests had the following general material properties: compression strength of the concrete after 28 days: 41 MPa (tests were carried out between 102 and 190 days after concreting), experimental yield strength of the steel reinforcing: 504 MPa, nominal width and thickness of the CFRP plate (Sika CarboDur S512): 50 mm and 1.2 mm, elastic modulus and tensile strength of the CFRP plate (given by manufacturer): 165’000 MPa and 3’100 MPa, the compression strength of adhesive (Sikadur-30) at 7 days: 103 MPa.

For the beam test, both conventional measurement techniques as well as an optical 3D image correlation system (ICS) [8] were used to measure the displacements at the tension face of the beam. Unlike the mechanical and electrical strain gauges, however, the ICS can capture displacements over a continuous length or surface. The 3D ICS with 4 mega pixel cameras, a 430 x 430 mm measurement field and a measurement accuracy of approximately 0.1 to 0.01 pixels, achieves a displacement accuracy of approximately 0.022 to 0.0022 mm. For the measurements with the ICS, eight positions for the cameras along the beam length were chosen. The cameras were fixed to a track and moved from position to position during which time the beam deflection was kept constant.

The CFRP strengthened beam was loaded deflection controlled. Several load cycles up to a mid-span deflection of 30 mm were performed, followed by loading up to failure.

3.2 Results

In Fig. 8 the strain pattern at two different load stages (stage 3 corresponded to a mid-span deflection of 10 mm, stage 7 corresponded to a mid-span deflection of 30 mm) in the constant shear region of the beam is shown. The development of the cracks as well as the crack spacing can be
seen, whereby the crack spacing corresponds approximately to the internal stirrup spacing of 10 cm.
Furthermore, it seems that additional cracks form under the CFRP plate (seen by the additional branches of the cracks near the plate), which may be a significant phenomenon in the modelling of the adhesively bonded CFRP plates. Further experimental and analytical investigations are required to better understand this effect.

Figure 9 shows the displacement in the x-direction (longitudinal direction of the CFRP plate) over the length of the beam at three load stages, 4, 7 and 18 (mid-span deflection: 15, 30, 40 mm) along three sections. One section (black line, section 0) was along the CFRP plate, one section along the concrete, close to the plate (red line, section 1) and one section also along the concrete, however, farther away from the plate (yellow line, section 2). During the test it was seen that the displacements in the x-direction were also influence by the fixed support. For this reason, the location of the fixed support was occasionally switched (from one support to the other) to prevent excessive movement in one particular direction.

The slip (the relative displacement between the CFRP plate and the concrete surface) was determined from the difference between the displacements in the x-direction of the plate (section 0) and the concrete (sections 1 or 2). It can be seen in Fig. 10 for load stage 18 and for the concrete section near the plate that a maximum slips in the range of 0.2 mm occurs in the pure flexural zone, whereby at the left plate end, constant slips in the range of approximately 0.15 mm and a maximum of also 0.2 mm can be observed.

![Fig. 8: Crack pattern in constant shear region for load stages 3 and 7.](image)

![Fig. 9: Slip between CFRP plate and concrete surface at three different load levels.](image)

In Fig. 10, the slip distribution shows not only high slips in the regions of the cracks, but also
unexpectedly high slip values at the plate ends. The slip distribution at the plate end can be characterised as approximately constant with small peaks (see no. 2 in the bottom graphic in Fig. 10) compared to the distinctive peaks at the cracks in the middle of the plate (see no. 1 in the bottom graphic in Fig. 10). From the results shown in Fig. 10 it is thought that the slip between the CFRP plate and concrete surface may be due to two different, yet superposing, effects: 1. slip due to cracking, and 2. slip due to the elastic and plastic deformation of the layered system. However, more experiments as well as analytical modelling is needed to confirm and understand this behaviour.

![Graph showing slip distribution](image)

Fig. 10: Slip between CFRP plate and concrete surface at three different load stages.

4. **Concluding remarks**

Steel and RC beams reinforced with adhesively bonded CFRP plates were subjected to four-point bending. Advanced optical measurement techniques—3D-digital speckle pattern interferometry and 3D image correlation—were employed to measure the displacement distribution near the end of the CFRP plate as well as over the length of the CFRP plate. A refined finite element analyses (FEA) of the strengthened steel beam was also carried out for comparison purposes.

- The DSPI measurement results were able to capture the strain (in particular, the shear strain) concentrations that have, up to now, only been shown analytically or using FEA. The magnitude of the measured strains have compared relatively well to the numerically obtained values. Furthermore, as has been done by a limited number of other authors, the FEA has shown much higher normal strains at the adhesive-steel (AS) interface than at the plate-adhesive (PA) interface, at the CFRP plate end. This difference has been suggested as the reason why debonding failure more commonly occurs at the AS interface rather than the PA interface.

- The 3D image correlation measurements showed the slip distribution along the length of the CFRP plate, with not only high slips in the regions of the cracks (as would be expected), but also unexpectedly high slip values at the plate ends. More experiments as well as analytical modelling is needed to confirm and understand this behaviour.

The optical measurement techniques presented here have shown the potential of measuring continuously over a surface, in order to produce a more complete picture of the displacement fields in the areas of interest such as in the vicinity of cracks and at the CFRP plate end. It is hoped that these types of measurements will aid in the refinement of the existing analytical solutions, which will, in turn, lead to more accurate debonding strength formulations and, consequently, design rules.
5. References


