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

Ann SCHUMACHER
Research Engineer
Empa
Dübendorf, Switzerland
ann.schumacher@empa.ch

Christoph CZADERSKI
Research Engineer
Empa
Dübendorf, Switzerland
chistoph.czaderski@empa.chk

Erwin HACK
Physicist
Empa
Dübendorf, Switzerland
erwin.hack@empa.ch

Masoud MOTAVALLI
Section Head / Prof.
Empa
Dübendorf, Switzerland
masoud.motavalli@empa.ch

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 on 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

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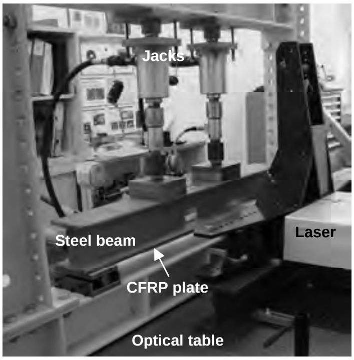
limited number of discrete measurement points are distributed along the length of the beam. For this reason, two recent test series have employed non-contact, full-field optical measurement methods in order to produce a more complete picture of the displacement fields in the areas of interest such as in the vicinity of cracks and at the carbon fibre reinforced polymer (CFRP) plate end.

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.



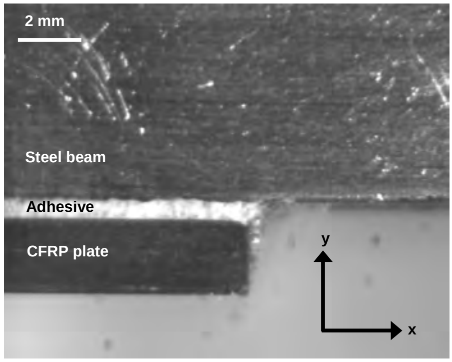


Fig. 1: DSPI experimental set-up (left); optical measurement area, 16x11 mm^2 (right)

2. Conclusions

- The DSPI measurements on small-scale steel beams reinforced with adhesively bonded CFRP plates 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 in this paper 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 carbon fibre reinforced polymer (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.