UPGRADING OF STEEL BEAMS USING COMPOSITE MATERIALS

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ABSTRACT

Research work has been conducted to study the effect of upgrading steel I-beams using carbon-fibre-reinforced-polymer (CFRP) plates bonded to the tension flange. The investigation comprised two sections; numerical analysis using Finite Element (FE) method and laboratory tests. The investigation was carried out as a parametric study where CFRP plates with different material and geometrical properties were used along with two different types of adhesive. The aim of the investigation was to study how various material properties of the strengthening material affect the behaviour of the strengthened steel I-beams. Additionally, the magnitude and distribution of the interfacial shear and peeling stresses in the strengthened beams were analysed. The results show that the moment capacity of the strengthened steel beam can be increased up to about 18%. It was also shown that yielding of the steel beam in the area of maximum moment does not affect the interfacial stresses near the end of the bond line, until excessive yielding and formation of plastic hinge.

KEYWORD

Strengthening, CFRP, interfacial stresses, steel beam.

INTRODUCTION

The interest for using alternative method to bolting or welding metallic plates for strengthening or repair of metallic beams has increased during the recent years. One attractive method, which has been studied during the last decade, is using prefabricated plates of carbon-fibre-reinforced-polymers. Some of the advantages with bonding CFRP plates are the strength and stiffness of the CFRP plates and that no additional stresses are introduced in the base material at installation. Additionally, it has been seen that the installation process of the strengthening system is less labour intensive and time consuming compared with traditional methods. Most of the research work carried out in this field comprises investigation of unsymmetrical steel beams, where the tension area is reduced due to deterioration and/or the compression side is increased by either additional steel plates or with a compositely acting concrete slab, see e.g. Miller et al. 2001, Tavakkolizadeh et al. 2003, Schnerch et al. 2004 and Al-Saidy et al. 2004. A general result from these studies shows that both the stiffness and the ultimate capacity in bending increased substantially for steel beams strengthened with CFRP plates.

The aims of the research work described in present paper were to investigate the behaviour of double symmetric steel sections strengthened with CFRP plates, in both the serviceability and ultimate limit state, and to analyse the interfacial stresses in the bond line between the beam and the bonded CFRP plate. The study was carried out as a parametric study on steel I-beams strengthened with CFRP plates bonded to the tension flange. The used CFRP plates had different material and geometrical properties, where each beam had its own unique configuration. The same beam configurations were investigated in both FE-analyses and laboratory tests and the results from these two methods were compared. The aims of the FE-analyses were to obtain information about the magnitude and distribution of the interfacial stresses in the bond line, which otherwise are difficult to measure on the tested specimens. The available analytical solutions with respect to the interfacial stresses (e.g. Smith et al. 2001, Deng 2004 and Stratford et al. 2006) are based on elastic theory, and it is of interest to study how the result from these analytical solutions agree with the results from the FE-analyses when the steel beam undergoes yielding.

FE-ANALYSES

The FE-analyses were carried out on five steel beams. Four of the beams were strengthened with bonded CFRP plates on the tension flange of the steel section and one was left unreinforced to serve as a reference beam. CFRP plates with different stiffness, strength and cross-section areas were used to evaluate how the different material
and geometrical properties affect the behaviour of the strengthened beams in both serviceability and ultimate limit state.

**Material and Geometrical Properties**

The investigated beams had an HEA 180 cross-section and a length of 2.0 metre. The steel material had yield strength of about 330 MPa, which was obtained from material tests conducted on specimens taken from the tested beams. The beams were provided with stiffeners over the supports and below the load application points. The free span of the beam was 1.8 metre and the length of the CFRP plate was 1.6 metre. A shorter length of the CFRP plate would result in an increase in magnitude of the interfacial stresses. The properties of the CFRP plates are given in Table 1. Four different configurations of the strengthening system were used, see Table 2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dimensions [mm]</th>
<th>$f_t$ [MPa]</th>
<th>E [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEA180</td>
<td>d=171, w_f=180, t_f=9.5, t_w=6</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>CFRP 1</td>
<td>1.4 x 81</td>
<td>3300</td>
<td>200</td>
</tr>
<tr>
<td>CFRP 2</td>
<td>1.8 x 50</td>
<td>1500</td>
<td>330</td>
</tr>
<tr>
<td>CFRP 3</td>
<td>2.4 x 60</td>
<td>3100</td>
<td>165</td>
</tr>
<tr>
<td>Epoxy 1</td>
<td>Thickness: ~2</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Epoxy 2</td>
<td>Thickness: ~2</td>
<td>30</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 2. Configuration of the laminates in the strengthened beams

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>CFRP laminate</th>
<th>Epoxy</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Ref</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam 1-2</td>
<td>CFRP 3</td>
<td>Epoxy 2</td>
<td>1</td>
</tr>
<tr>
<td>Beam 1-3</td>
<td>CFRP 1</td>
<td>Epoxy 1</td>
<td>1</td>
</tr>
<tr>
<td>Beam 1-4</td>
<td>CFRP 1</td>
<td>Epoxy 1</td>
<td>1 and 2</td>
</tr>
<tr>
<td>Beam 1-5</td>
<td>CFRP 2</td>
<td>Epoxy 1</td>
<td>1</td>
</tr>
</tbody>
</table>

In three of the analysed beams the CFRP plates were bonded to the lower surface of the tension flange, and in one the CFRP plates were bonded to both upper and lower surface of the tension flange. The position of the CFRP plates for each analysed beam is given in Table 2 and the positions are illustrated in Figure 1.

**FE Model**

In the FE model, the steel beam, adhesive and CFRP plate were all modelled with 20-nodes solid elements (C3D20R) and with full interaction between all parts. The material model for the steel material was non-linear and obtained from material tests, while the adhesive and CFRP plate were assumed to have a linear elastic behaviour. Only one quarter of the beam had to be modelled due to the longitudinal and transversal symmetry planes, see Figure 2.
Figure 2. Geometry of the FE-model

The effects of residual stresses and initial imperfections caused by the fabrication process were not taken into consideration in the FE model. Through the non-linear analysis, loading was done according to a schedule, which was determined and managed in prescribed steps. To capture the concentration of the interfacial stresses near the end of the bond line, the model was meshed with quite dense mesh in those regions. A convergence study, with reference to the mesh size, was then conducted to obtain the densest mesh that giving reliable results.

LABORATORY TESTS

Beam specimens with the same configurations investigated in the FE-analyses described in the previous section were prepared and tested in the laboratory. All strengthened beams were sand blasted and cleaned over the region where the CFRP plate would be applied, and immediately afterward coated with a primer. The adhesive was applied to the CFRP plate in a v-formed shape to minimize the presence of air gaps in the adhesive layer at installation. The CFRP plate was then immediately attached to the steel beam.

Test Setup

Each beam was provided with strain gauges (SG), which were positioned according to Figure 3. To capture the strain distribution and derive the shear stresses near the end of the bond line a series of ten strain gauges, with 1 mm in between, was attached on the CFRP plate. The beams were then tested in four-point bending with loading controlled by deformation. The deflection in mid-span was measured with a LVDT.

Figure 3. Illustration of test setup

RESULTS

Global Behaviour

The global response of the investigated beams is shown in Figure 4. Figure 4a shows the load-strain behaviour of the beams tested in the laboratory. The maximum obtained increase in moment capacity was around 18%, which were reached for the beams strengthened with high strength CFRP plates. These two beams showed also the highest ductility. The failure mode of these beams was rupture of the CFRP plates. Flange buckling in the area of constant moment were visible before the CFRP plates got to rupture. Figure 4b show a comparison between the results obtained from the FE-analysis and the laboratory test for one of the investigated strengthened beams, and the two results show a good agreement.
A study of the normal (bending) stresses over the height of the steel section in the FE-analyses and the laboratory tests shows that the level of the neutral axis moves towards the tension flange as the load increased. The stress distribution over the height of the steel section for different load levels is plotted in Figure 5 along with the results obtained from one of the strengthened beams investigated with FE-analysis. The figure shows that the CFRP plate had to take an increased part of the tensile forces to compensate for the increased area in compression.

Figure 5: Normal stress distribution over the height of the strengthened steel section for different load levels.

**Interfacial Stresses**

Prior to the laboratory tests and the FE-analyses, a prediction of the magnitude and distribution of the interfacial shear and peeling stresses was made for all investigated strengthened beams by using an available analytical solution (Smith et al. 2001). A comparison between the results obtained from the analytical solution and the stresses derived from the laboratory investigation showed an overall agreement, but the derived stresses from the measured data had some disparities due to errors in the experimentally recorded data, see Linghoff et al. 2006.

In the FE-analyses it was found that the distribution of the interfacial shear and peeling stresses was not constant over the width of the bond line, which otherwise is the assumption adopted in all analytical solutions. The distribution of shear stress along the width of the bond line at the end of the CFRP plate, obtained from FE-analysis and analytical solution, are given in Figure 6 for one of the investigated beams at a specific load level. This difference in stress distribution is seen over the whole stress transference length along the bond line. The peeling stress shows the same behaviour as the shear stress in Figure 6, both over the width and along the bond line.
The available low-order analytical solutions for prediction of the interfacial shear and peeling stresses are developed based on the theory of elasticity. In Figure 7a, the interfacial shear stress from the analytical solution (Smith et al. 2001) and those predicted by FE-analysis are shown for one of the strengthened beams, plotted as a function of magnitude of applied load. The extracted values were taken close to the end of the bond line and at a width of the bond line where the results from the two analyses coincident, c.f. the discussion connected to Figure 6 above. The plot in Figure 7a shows that the results from the FE-analysis and the analytical solution have a good agreement over the whole load range, and are not affected by yielding in the steel beam near the midspan, which starts at an applied load of about 200 kN. Figure 7b shows the same comparison for the same beam, but between the results obtained from the FE-analysis and the laboratory test. The laboratory test showed, for all tested strengthened beams, that the shear stress near the end of the bond line starts to decrease at a load range causing a plastic hinge in the steel beam. The reason for this decrease in shear stress near the end of the bond line has not yet been fully understood.

The interfacial shear stress distributions near mid-span of the strengthened beams have been extracted from the FE-analysis for one of the investigated beams, and are plotted in Figure 8. The curves in the plot represent the interfacial shear stress distribution at different load levels. These load levels caused that the steel section was well in different plastic phases near the mid-span of the beam. This involves that in the area where the steel transitions from plastic to elastic behaviour a transference zone arise. In this zone forces in the CFRP plate will be transferred to the steel flange, and when the yielding area increases as the applied load increases, the transference zone will be moved in a direction away from the mid-span. The result can be seen in Figure 8. The movement of the location of maximum shear stress will end up when a plastic hinge has developed, so instead of increasing the area of yielding the deformations will increase in the plastic hinge, which brings out that the magnitude of the interfacial stresses will continue to increase in the same point. The FE model was not created with any failure criterions, and that is why the interfacial shear stress in the plot was able to reach such high values.
CONCLUSIONS

The study shows that it is possible to reflect the behaviour of a steel I-beam strengthened with bonded CFRP plate with a 3-dimensional solid element model in FE-analysis. The advantages with using a solid element model is that the interfacial stress distribution can be investigated both in the longitudinal and transversal direction of the bond line. The study also showed that it is possible to increase the moment capacity of a double symmetric steel section up to about 18%. This was achieved for beams strengthened with high strength CFRP plates and these beams also showed the highest ductility. To increase the capacity further the compressed flange has to be strengthened to. The general failure mode in the strengthened beams tested in laboratory was rupture of the CFRP plate.

Experiences from the laboratory tests showed that it was hard to obtain measured strain values without small disturbances, which cause large fluctuations in the distribution of the shear stress obtained from derivations of the measured strains. The FE-analyses showed that the interfacial stresses vary along the width of the bond line, with the maximum values near the location below the web-plate, where the section is stiffest. Thus, for a steel section with non-constant stiffness along the width of the section the available analytical solution may give too low values of the interfacial shear and peeling stresses compared with the results obtained from the FE-analysis.

The investigation also showed that the shear stress development as a function of applied load will have good agreement between the results from the analytical solution and the FE-analysis, even after the steel section has reached yielding. This shows that the interfacial stresses near the end of the bond line are not affected by the yielding of the steel section in the area of maximum moment.

In the plastic phase of a strengthened steel beam, shear stresses will arise in the area adjacent to the yielding zone, and the location for the maximum value of the interfacial shear stress will move away from mid-span of the beam as the area in yielding increases. The magnitude of maximum shear stress in the adhesive will at higher degrees of plastic behaviour of the steel beam reach values well above the capacity of the adhesive.

REFERENCES