FLEXURAL CAPACITY OF COMPOSITE BEAMS WITH AN INCREASED AREA OF BONDED STEEL PLATES

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The objectives of this research study is to demonstrate the increase in the flexural resistance of composite beams and to compare the theoretically calculated to the experimentally tested flexural capacity of reinforced concrete beams and composite beams. Four similar reinforced concrete beams were constructed for this research study with dimensions of 250 mm wide and 450 mm deep. The beams were reinforced with 2 Y12 bars in both the tension and compression zones and the concrete compressive strength ($f_{cm}$) was 34.5 MPa. The beams span 4500 mm and were loaded at third spans. A control beam (Contr), without a bonded plate form the base for the flexural strength comparison to three composite beams (CB). CB1 were strengthened with a 75 mm x 2 mm, CB2 with a 75 mm x 3 mm and CB3 with a 75mm x 4mm 350 W steel plate. The concrete surface was prepared by scabbling to expose the well-bonded large aggregate and the steel plate was dry grit blasted to a white metal finish to obtain a 100–140 µm blast profile. The steel plate was bonded to the concrete surface by means of Pro-Struct 618LV primer and Pro-Struct 617NS epoxy. The flexural resistance of composite beams increase as the cross-sectional area of the bonded plate increase. From control to composite beams is 40.46% for CB1, 64.77% for CB2 and 93.22% for CB3. Comparing the accuracy of the theoretically calculated to the experimentally tested flexural capacity is 0.02% for CB1, 0.04% for CB2 and 2.34% for CB3.

Keywords: Moment, Reinforced concrete, Experimental study, Epoxy.

1 INTRODUCTION

Additional reinforcement externally bonded to existing reinforced concrete flexural members is required to replace corroded reinforced bars or to add reinforcement in order to increase the flexural resistance due to increased applied loading. The objective of this research study was to demonstrate the increase in the flexural resistance of composite beams with an increased cross-sectional area of bonded steel plates, and to draw comparisons between the theoretically calculated and the experimentally tested failure loads of the flexural members.

2 EXPERIMENTAL PROGRAM

Four existing reinforced concrete beams with dimensions of 4,800 mm x 250 mm wide x 450 mm deep were used for this research study. The beams were supported at 150 mm from both ends, leading to a span length of 4500 mm. The reinforcement consists of 2 high strength ($f_y - 450$ MPa) 12 mm diameter bars in both the compression and tension zones and mild steel ($f_y - 250$ MPa) 8 mm diameter stirrups spaced at 200 mm. Cores drilled indicates an average concrete strength ($f'_c$)
of 27.6 MPa which relates to a cube strength \( f_{cu} \) of 34.5 MPa. Figure 1 indicates a cross section and long section of the loaded beam.

![Figure 1. Cross section and long section of the loaded beam.](image)

The surface preparation of the concrete beams was done by scabbling in order to expose the large aggregate. This scabbled concrete surface was primed with Pro-Struct 618LV to create a bonding layer for the Pro-Struct617NS epoxy. The curing time as recommended by the manufacturer of the Pro-Struct617NS epoxy, is 7 days.

![Figure 2. Completed composite beam.](image)

The surface of the steel plates was sandblasted to a white metal finish to obtain a 100-140 µm blast profile which must be kept clean from dust and oil contamination to ensure a clean bonding surface. Figure 2 shows a complete composite beam with the steel plate bonded to the reinforced concrete beam.

The following beams were used for this research study. All bonded steel plates are of grade 350W:

- Control beam (Contr) is un-plated.
- Composite Beam 1 (CB1) fitted with 1 x 75 mm wide x 2 mm thick plate.
- Composite Beam 2 (CB2) fitted with 1 x 75 mm wide x 3 mm thick plate.
- Composite Beam 3 (CB3) fitted with 1 x 75 mm wide x 4 mm thick plate.
Figure 3 shows a beam during testing. The loads were applied at one-third spans in order to imitate a uniformly distributed load (UDL) load.

![Loaded beam with 1/3 span loading.](image)

3 ANALYSIS OF FLEXURAL COMPOSITE ELEMENT

This research study focused on the intermediate crack (IC) debonding mechanism. Due to flexure in the beam under loading, vertical IC develops on the tension side of the beam. Once these cracks intercept the bonded steel plate, localized horizontal interface debonding cracks between the concrete surface and the bonded plate occur, as indicated in Figure 4. Initially these interface cracks are localized around the IC and have no effect on the flexural strength of the composite beam. However, if the load increases and the IC cracks widen, the interface cracks grow horizontally longer and when meeting one another debonding of the plate occurs, which is referred to as the IC debonding mechanism.

![Intermediate cracking debonding mechanism.](image)

The design procedure of composite beams is described below with the help of Figure 5. Figure 5.1 shows the cross-section of a composite beam, indicating the bonded steel plate and reinforcement bars. Figure 5.2 indicates the possible strain pivotal points about which the strain profile rotates.

1. Compression zone concrete failure strain ($\varepsilon_c=0.0035$)
2. Tension zone failure strains:
   - Strain in the rebar ($\varepsilon_{rebar}$)
Fracture strain of the bonded plate ($\varepsilon_{frac}$)

- Debonding strain between the plate and the concrete ($\varepsilon_{db}$)

The debonding strain between the plate and the concrete ($\varepsilon_{db}$) is determined by means of a push-pull test. This procedure is described by Oehlers et al. (2008) in HB 305-2008 Design Handbook for RC Structures retrofitted with FRP and Metal Plates: Beams and Slabs.

Figure 5.3 is the strain diagram pivoting around the debonding strain between the plate and the concrete ($\varepsilon_{db}$). It was found in this research study that the appropriate pivoting point was around the concrete failure strain $\varepsilon_c=0.0035$.

Figure 5.4 indicates the compressive and tension stresses that can be obtained from the guessed strain profile indicated in Figure 5.3 as the elasticity module of the concrete and steel plates is known.

The resultant forces are indicated in Figure 5.5. These were calculated by computing the obtained stress with the cross-section areas on which they are exerted. To achieve an equilibrium of compressive and tensile forces, the inclination of strain graph is repeatedly re-guesed. Once an equilibrium of the compressive and tensile forces is reached, the moment resistance can be calculated by taking moment around any point of the internal couple.

![Figure 5.1. Cross-Section](image1)

![Figure 5.2. Possible strain pivotal points](image2)

![Figure 5.3. Strain graph pivoting around concrete strain](image3)

![Figure 5.4. Stress graph](image4)

![Figure 5.5. Force graph](image5)

Figure 5. Strains, stresses and forces of a composite flexural member.

## 4 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS OF FLEXURAL COMPOSITE ELEMENTS

The theoretically calculated flexural strength of the beams is given in Table 1.

<table>
<thead>
<tr>
<th>Beam name</th>
<th>Number, width, and thickness of steel plate (mm)</th>
<th>Theoretically calculated moment (kNm)</th>
<th>% Increase to control beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contr</td>
<td></td>
<td>41.59</td>
<td></td>
</tr>
<tr>
<td>CB1</td>
<td>1 x 75 x2</td>
<td>63.52</td>
<td>52.73%</td>
</tr>
<tr>
<td>CB2</td>
<td>1 x 75 x 3</td>
<td>74.49</td>
<td>79.12%</td>
</tr>
<tr>
<td>CB3</td>
<td>1 x 75 x 4</td>
<td>85.47</td>
<td>105.51%</td>
</tr>
</tbody>
</table>
The experimental results are indicated in Figure 6. The increase in the load bearing capacity from the control beam to the composite beams is evident.

![Flexural Strengthening Experimental Results](image)

Figure 6. Experimentally determined load deflection graph.

The experimental moment was determined by applying the experimental load on third spans as shown in Figure 1. The own weight of the reinforced concrete beam was considered as 24 kN/m³ and the load spreader as 1.34 kN.

Table 2 indicates the experimentally determined load and calculated moment and Table 3 compares the theoretically calculated and experimentally determined moments.

**Table 2.** Experimentally determined flexural resistance and percentage increase.

<table>
<thead>
<tr>
<th>Beam name</th>
<th>Number, width and thickness of steel plate (mm)</th>
<th>Experimental load (kN)</th>
<th>Experimentally determined moment (kNm)</th>
<th>% Increase to control beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contr</td>
<td></td>
<td>49.19</td>
<td>45.23</td>
<td></td>
</tr>
<tr>
<td>CB 1</td>
<td>1 x 75 x 2</td>
<td>73.59</td>
<td>63.53</td>
<td>40.46%</td>
</tr>
<tr>
<td>CB 2</td>
<td>1 x 75 x 3</td>
<td>88.25</td>
<td>74.52</td>
<td>64.77%</td>
</tr>
<tr>
<td>CB 3</td>
<td>1 x 75 x 4</td>
<td>105.41</td>
<td>87.39</td>
<td>93.22%</td>
</tr>
</tbody>
</table>

**Table 3.** Comparison between theoretically calculated and experimentally determined flexural resistance.

<table>
<thead>
<tr>
<th>Beam name</th>
<th>Number, width and thickness of steel plate (mm)</th>
<th>Theoretically calculated moment (kNm)</th>
<th>Experimentally determined moment (kNm)</th>
<th>% Difference of theoretical to experimental moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contr</td>
<td></td>
<td>41.59</td>
<td>45.23</td>
<td></td>
</tr>
<tr>
<td>CB 1</td>
<td>1 x 75 x 2</td>
<td>63.52</td>
<td>63.53</td>
<td>0.02%</td>
</tr>
<tr>
<td>CB 2</td>
<td>1 x 75 x 3</td>
<td>74.49</td>
<td>74.52</td>
<td>0.04%</td>
</tr>
<tr>
<td>CB 3</td>
<td>1 x 75 x 4</td>
<td>85.47</td>
<td>87.39</td>
<td>2.34%</td>
</tr>
</tbody>
</table>
5 SUMMARY

The experimental results of the tests reveal that using externally bonded steel reinforcement is an efficient technique to increase the flexural capacity of reinforced concrete beams. An increase in the moment capacity of the composite beams in relation to the control of as high as 93% is obtained, as indicated in Table 2.

The comparison of the theoretical and experimental moments is shown in Table 3, these values are within 3% which is an indication of the accuracy of HB 305-2008 Design Handbook for RC Structures retrofitted with FRP and Metal Plates: Beams and Slabs (Oehlers et al. 2008).

References