THE FLEXURAL CAPACITY OF COMPOSITE BEAMS WITH EXTERNAL AND SIDE-MOUNTED PLATES

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In the case of increased loading on an existing reinforced concrete structure, an effective method to strengthen the flexural members is to adhesively bond steel plates to the tension surface of the reinforced concrete flexural member, creating a composite flexural member. These plates can be bonded to various positions on the 2ssoffit, or side-mounted (SM) vertically to the reinforced concrete flexural members. This research study verified the mathematical model which predicts the flexural capacity of composite beams by comparing it to the results of the experimentally tested specimens. The results are within 1% for the EB and 3% for the SM composite flexural members. The experimental results indicate an increase of 63% in the flexural resistance of the EB and 53% in the SM composite members compared to non-strengthened reinforced concrete members. The experimental results also indicate that the flexural resistance of the EB member is 6% higher than that of the SM member.

Keywords: Moment resistance, Mathematical modelling, Stress graph, Reinforced concrete.

1 INTRODUCTION

The purpose of existing reinforced concrete structures might change, resulting in applied loads exceeding the original design load. Also, when reinforced concrete structures are renovated due to rust on the reinforcement bars resulting in a decreased bar diameter. A solution to the above drawbacks is to strengthen existing reinforced concrete flexural members by means of adhesively bonding steel plates to the tension surface, thus creating composite beams. These plates, bonded to the tension surface, fulfill the same purpose as tension reinforcement bars embedded within the concrete, except that an additional failure mode of plate debonding occurs. Plates can be bonded to various positions on the flexural members. This research study verified the mathematical model which predicts the flexural capacity of composite members by comparing the results to experimentally tested specimens. The experimentally measured flexural resistances of the EB and SM composite members were also compared.

2 EXPERIMENTAL PROGRAM

Six (6) reinforced concrete members were constructed for this research study with dimensions of 250 mm wide, 450 mm deep and 4.8 m long. The reinforcement for all beams consists of 2 high-yield 10 mm diameter bars in the compression zone, 2 high-yield 12 mm diameter bars in the tension zone, and 10 mm diameter mild steel stirrups spaced at 250 mm for shear.
The properties of the materials used were as follows:

(i) The concrete strength ($f_{cu}$) was 25.04 MPa, SD of 1.401, using 100 mm cubes.
(ii) The concrete modules of elasticity ($E_c$) were 29.2 GPa, SD of 1.461, using 150 mm cylinders.
(iii) The yield stress of the high-yield reinforcement bar ($f_y$) was 488.6 MPa and the yield strain was ($e_y$) 0.00244. The SD was 1.388.
(iv) The mild steel plates were of grade 350W. The yield stress ($f_y$) was 393.4 MPa and the yield strain ($e_y$) was 0.00197. The SD was 1.398.

The surface of the composite concrete beams was prepared by means of scabbling to expose the large aggregate. This scabbled surface was primed with Pro-Struct 618LV which penetrated the concrete to form a bonding layer for the Pro-Struct 617NS epoxy. The surface of the steel plate was sandblasted to a white metal finish to obtain a 100-140 µm blast profile. The surface was kept clean from dust and oil contamination to ensure a sound bonding surface.

The following flexural members were constructed for this research study, see Fig. 1.

(i) 1 x un-plated Control member (Contr)
(ii) 2 x Composite members with EB plate (EB1 and EB2) fitted with 1 x 100 mm wide x 3 mm thick steel plate.
(iii) 3 x Composite members with SM plates (SM1 to SM3) fitted with 2 x 50 mm wide x 3 mm thick steel plates.

![Figure 1a](image1a.png) ![Figure 1b](image1b.png) ![Figure 1c](image1c.png)

**Fig. 1.** Cross-sections and long section of the composite members.
3 MATHEMATICAL MODEL DETERMINING THE FLEXURAL RESISTANCE OF COMPOSITE FLEXURAL MEMBERS

The HB-305-2008 Design Handbook for RC Structures Retrofitted with FRP and Metal Plates: Beams and Slabs (Oehlers et al. 2008), and the Design of FRP and Steel Plated RC Structures (Oehlers and Smith 2004) both describe the mathematical model for determining the flexural resistance of composite flexural members. Fig. 2 describes the mathematical model for EB and Fig. 3 describes that for SM composite flexural members.

Fig. 2a (EB) and Fig. 3a (SM) indicate the cross-sections of the composite beams showing the bonded steel plates and reinforcement bars.

Fig. 2b (EB) and Fig. 3b (SM) indicate the possible strain pivotal points about which the strain profile can rotate.

(i) The concrete failure strain ($\varepsilon_c = 0.0035$) in the compression zone
(ii) In the tension zone the following failure strains:
   (a) Fracture strain in the rebar ($\varepsilon_{\text{rebar}} = 0.0027$)
   (b) Fracture strain of the bonded plate ($\varepsilon_{\text{frac}} = 0.0022$)
   (c) Debonding strain between the concrete and the steel plate is taken as ($\varepsilon_{db} = 0.0045$) obtained from Table 2.2 in Oehlers et al. (2008).

Fig. 2c (EB) and Fig. 3c (SM) show the strain diagram pivoting around the concrete failure strain ($\varepsilon_c$). This was found to be the first strain failure mode.

Fig. 2d (EB) and Fig. 3d (SM) show the compressive and tension stresses. These were obtained from the strain profile by multiplying it by the elasticity modules of concrete or steel.

The resultant forces are indicated in Fig. 2e (EB) and Fig. 3e (SM). These forces were determined by multiplying the stresses by the relevant cross-sectional areas on which they are exerted. To achieve an equilibrium of compressive and tensile forces, the inclination of strain graph is repeatedly re-altered. Once an equilibrium of the compressive and tensile forces is reached, the moment resistance can be calculated by multiplying the forces to the offset distances from the neutral axis as shown in Fig. 2e and Fig. 3e.

Fig. 2. Strains, stresses and forces of an EB composite flexural member.
Fig. 3. Strains, stresses and forces of an SM composite flexural member.

4 COMPARISON BETWEEN THE EXPERIMENTAL FLEXURAL RESISTANCE OF EB AND SM COMPOSITE FLEXURAL MEMBERS

Fig. 4 presents the experimentally determined load-deflection graph of the Control beam and the two EB composite beams. The increase in flexural capacity from the Control to the EB composite slabs is evident.

Fig. 4. Experimental results of the Control and EB flexural members.

Fig. 5 indicates the experimentally determined loads and deflections of the Control member and the three SM composite members.
It is worth noting the difference in ductility between the EB and SM composite flexural members. The EB steel plates of the composite flexural members debond at approximately 230 mm deflection, as shown in Fig. 4, and those of the SM composite flexural members debond at approximately 120 mm deflection, as shown in Fig. 5.

The first failure mode to be observed was the failure of the concrete in the compression zone of the flexural member. The pivotal point of the strain diagram should therefore be around the concrete failure strain ($\varepsilon_c = 0.0035$)

The experimentally measured point loads of the Control beam, and of the EB and SM composite flexural members, as well as the percentage increases, are given in Table 1.

Table 1. Experimentally measured point loads of the Control, EB and SM members.

<table>
<thead>
<tr>
<th>Member Name</th>
<th>$P_{\text{contr}}$ (kN)</th>
<th>$P_{EB}$ (kN)</th>
<th>$P_{SM}$ (kN)</th>
<th>Ratio $P_{EB}/P_{\text{contr}}$</th>
<th>Ratio $P_{SM}/P_{\text{contr}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contr</td>
<td>70.03</td>
<td>112.94</td>
<td>106.94</td>
<td>1.61</td>
<td>1.53</td>
</tr>
<tr>
<td>EB1</td>
<td></td>
<td>114.69</td>
<td></td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>EB2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SM1</td>
<td>108.49</td>
<td></td>
<td></td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>SM2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM3</td>
<td>107.11</td>
<td></td>
<td></td>
<td>1.53</td>
<td></td>
</tr>
</tbody>
</table>

The average experimentally measured applied point load ($P_{EB}$) for the EB composite flexural members is 113.82 kN and the average applied point load ($P_{SM}$) for the SM composite flexural members is 107.51 kN. The flexural capacity of the SM members is therefore 5.9% less than that of the EB composite flexural members. This lower flexural capacity can be attributed to the smaller lever arm ($x_3$) of the internal couple, indicated in Fig. 2e for the EB and in Fig. 3e for the SM composite flexural members.
5 COMPARISONS BETWEEN THE MATHEMATICAL MODEL AND THE EXPERIMENTALLY MEASURED FLEXURAL CAPACITY

Table 2 compares the flexural resistance of the experimentally measured flexural members to the mathematical model’s predictions for both the Control, EB, and SM composite members.

Table 2. Experimentally measured point loads compared to the mathematical model.

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Experimentally Measured Load</th>
<th>Mathematical Model Load</th>
<th>Ratio ( P_{\text{experimental}} / P_{\text{mathematical}} )</th>
</tr>
</thead>
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<tr>
<td>Contr</td>
<td>70.03</td>
<td>49.46</td>
<td>1.42</td>
</tr>
<tr>
<td>EB1</td>
<td>112.94</td>
<td>114.29</td>
<td>0.99</td>
</tr>
<tr>
<td>EB2</td>
<td>114.69</td>
<td>114.29</td>
<td>1.00</td>
</tr>
<tr>
<td>SM1</td>
<td>106.94</td>
<td>110.20</td>
<td>0.97</td>
</tr>
<tr>
<td>SM2</td>
<td>108.49</td>
<td>110.20</td>
<td>0.98</td>
</tr>
<tr>
<td>SM3</td>
<td>107.11</td>
<td>110.20</td>
<td>0.97</td>
</tr>
</tbody>
</table>

The accuracy between the experimentally measured point loads and the mathematical model’s point load is within 1% for the EB composite beams and within 3% for the SM composite flexural member. The average experimentally measured point load of the EB composite flexural member (113.82 kN) is higher than the SM point load of 107.51 kN. This is a result of the larger lever arm of the EB flexural member than that of the SM member, as mentioned before.

6 SUMMARY

The experimental results indicate an increase of 63% in the flexural resistance of the EB and 53% in that of the SM composite members compared to non-strengthened reinforced concrete members. Creating composite flexural members by bonding external reinforcement is therefore an efficient technique to increase the flexural capacity. The challenges of increased applied loads on existing reinforced concrete structures and of renovations due to rusting of the reinforcement bars can be successfully overcome.

The experimentally measured point loads compared to the mathematical model are within 1% for the EB composite beams and within 3% for the SM composite beams. This is a clear indication of the accuracy of mathematical model.

The experimentally measured point load of the EB composite flexural member (113.82 kN) is higher than the point load of 107.51 kN of the SM member. This is a result of the larger lever arm of the EB flexural member than of the SM composite flexural member.

References
