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Published in:
Early-age cracking and serviceability in cement-based materials and structures

Publication date:
2017

Document Version:
Final published version

Citation for published version (APA):
Understanding the influence of externally bonded TRC on the cracking behaviour of a plain concrete beam

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ABSTRACT

In the last decennia there is an increasing interest in the use of external reinforcement for concrete structures made of both Fibre Reinforced Polymers (FRP) and Textile Reinforced Cementitious composites (TRC). Especially for TRC, one of the main applications could be the crack control within the concrete substrate. Despite numerous studies in this field, the influence of an external TRC layer on the cracking behaviour of the concrete substrate is not yet known. In order to study the basic principles of this interaction, externally reinforced plain concrete beams are experimentally analysed in this paper. More in particular, the influence of the pre-treatment type of the concrete surface is studied, together with the influence of the contact width between the TRC and the concrete. Finally, also a validation of the TRC versus the more established CFRP technique will be performed. The experimental results indicate the need for a pre-treatment of the concrete substrate prior to the application of the TRC, although the exact pre-treatment type has no influence. Additionally, the beneficial influence of enlarging the contact width between the TRC and the concrete substrate on the loadbearing capacity as well as on the crack width are illustrated. These observations in this paper confirm the applicability of a TRC for crack control of the concrete substrate and provide a deeper insight in the basic mechanisms controlling this cracking behaviour.

Keywords: External reinforcement, TRC, cracking behaviour, bending

1. INTRODUCTION

Recently there is an ever increasing interest in the use of high performance Textile Reinforced Cementitious composites (TRC) for structural applications like stay-in-place formwork [1] and strengthening and repair of concrete structures [2, 3, 4, 5]. One of these high performance TRCs is IPC TRC, based on an Inorganic Phosphate Cement matrix and E-glass fibres. IPC TRC has already proven its capabilities as a material for structural stay-in-place formwork [6, 7, 8] and external strengthening [9] of concrete beams. These studies revealed that the initial uncracked stiffness of the concrete beam is retained far above the calculated and measured cracking moment. This increased stiffness can be very interesting in cases where the serviceability limit state of deflection is governing the (re)design. However another important serviceability limit state parameter is the cracking behaviour of the concrete substrate. To gain knowledge on this particular topic four point bending tests are executed on several series of plain concrete beams, externally reinforced with IPC TRC and monitored with Digital Image Correlation (DIC) to visualize the crack pattern evolution.

2. EXPERIMENTAL PROGRAM

2.1 Test set-up

The specimens are tested in a four point bending test with third point loading (Figure 1). The loading is displacement controlled with a displacement rate of 0.2 mm/min, using a servo-hydraulic actuator (Instron 5885H).

![Figure 1](image1.png)

Figure 1. A four point bending test with third point load is performed on the externally reinforced beams.

During the bending test the behaviour of the beams is monitored using a linear variable differential transformer (LVDT)

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placed in the middle of the span underneath the beam. The crack pattern evolution is followed using the Digital Image Correlation (DIC) technique, which is a non-contacting optical measuring technique. Displacements can be measured by the comparison of subsequent surface pictures taken from a speckle pattern of black spots on a white background, which is applied on the specimens. Out of the displacement field, the strains can be calculated. One pair of cameras follows the side of the beam and another pair of cameras the bottom. Both systems are able to measure the zone of constant moment, a window of approximately 200 mm wide in the middle of the beam.

2.2 Specimen types

32 specimens of 11 different specimen types are tested. The number of specimens per type is indicated in the 6th column of Table 1. Considering a very similar behaviour between identical specimens and to maintain the overview only one representative beam will be used to illustrate the observations.

The first parameter that is varied in this paper is the concrete surface treatment, prior to the application of the external reinforcement. For all beams where a pre-treatment is performed, the laitance layer of more or less 10 mm is removed using a diamond saw such that the granulates are reached for all beams (“Diamond saw”). The chemical treatment consisted of the application of a 12% HCl-solution during 15 minutes, cleaning the beam with water and neutralizing the reaction using a 1% ammoniac solution (“Chemical”). An extra roughening is obtained by hitting the beam with a pick (“Roughened”). These pre-treatments result in an increasing roughness of the beam surface.

The second parameter that is studied is the influence of the contact width. Therefor two times two beam types are created with an identical cross-section of external reinforcement, but with a different contact width. The word “full” in Table 1 indicates that the entire bottom surface of the concrete is covered with external reinforcement; analogically, “half” indicates that half of the width in the centre of the concrete is covered. An exact number indicates the width expressed in mm.

The third and final parameter is the reinforcing material, which is either IPC TRC either CFRP.

Table 1. Specimen types

<table>
<thead>
<tr>
<th>Beam</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>Pre-treatment</th>
<th>#</th>
<th>Concrete strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-F-N</td>
<td>IPC TRC</td>
<td>4</td>
<td>Full</td>
<td>None</td>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>B-F-DS</td>
<td>IPC TRC</td>
<td>4</td>
<td>Full</td>
<td>Diamond saw</td>
<td>6</td>
<td>Low</td>
</tr>
<tr>
<td>B-F-CT</td>
<td>IPC TRC</td>
<td>4</td>
<td>Full</td>
<td>Chemical</td>
<td>4</td>
<td>Low</td>
</tr>
<tr>
<td>B-F-ER</td>
<td>IPC TRC</td>
<td>4</td>
<td>Full</td>
<td>Roughened</td>
<td>4</td>
<td>Low</td>
</tr>
<tr>
<td>I4-F-DS</td>
<td>IPC TRC</td>
<td>2</td>
<td>Full</td>
<td>Diamond saw</td>
<td>3</td>
<td>Normal</td>
</tr>
<tr>
<td>I4-H-DS</td>
<td>IPC TRC</td>
<td>4</td>
<td>Half</td>
<td>Diamond saw</td>
<td>3</td>
<td>Normal</td>
</tr>
<tr>
<td>I4-F-DS</td>
<td>IPC TRC</td>
<td>3</td>
<td>Full</td>
<td>Diamond saw</td>
<td>4</td>
<td>Normal</td>
</tr>
<tr>
<td>I12-H-DS</td>
<td>CFRP</td>
<td>6</td>
<td>Half</td>
<td>Diamond saw</td>
<td>4</td>
<td>Normal</td>
</tr>
<tr>
<td>C-14-DS</td>
<td>CFRP</td>
<td>1.2</td>
<td>14</td>
<td>Diamond saw</td>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>C-40-DS</td>
<td>CFRP</td>
<td>1.2</td>
<td>40</td>
<td>Diamond saw</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>C-F-DS</td>
<td>CFRP</td>
<td>1.2</td>
<td>Full</td>
<td>Diamond saw</td>
<td>1</td>
<td>Low</td>
</tr>
</tbody>
</table>

2.3 Materials

Concrete

For the first and third series a low strength concrete (simulating the conditions of an old building, needing external strengthening) is designed with mass proportions: 220 kg Portland cement CEM II 32.5N; 80 kg fly ash; 165 l water; 482 kg sand (0/2); 482 kg gravel (4/6) and 896 kg gravel (6.5/14). Resulting in an experimental compressive strength of 16.8 MPa, Young modulus of 28.2 GPa and modulus of rupture of 3.5 MPa after 14 days of age (age of testing).

For the second series a normal strength concrete is used with mass proportions: 375 kg Portland cement CEM II 32.5N; 210 l water; 690 kg sand (0/2) and 1125 kg gravel (6.5/14). Resulting in an experimental compressive strength of 30.0 MPa, Young modulus of 32.8 GPa and modulus of rupture of 4.3 MPa after 20 days of age (age of testing).

TRC: IPC TRC

The TRC used in this paper consists of an Inorganic Phosphate Cement (IPC) reinforced with an E-glass fibre textile. The matrix material IPC is mixed in the mass proportions of 1 vubonite liquid component and 0.82 high performance vubonite powder. This IPC matrix is reinforced by hand lay-up with randomly in-plane oriented fibre textiles, being glass fibre chopped strand mats Vetrotex M5, with a surface density of 300 g/m². The laminates have an experimental fibre volume fraction of 22 %, a tensile strength of 39.5 MPa, an ultimate strain of 0.9 %, a Young modulus of 12.2 GPa for the first linear elastic zone and a Young modulus of 4.2 GPa for the second linear zone.

FRP: CFRP
A commercially available CFRP strip is used [10] (tensile test: tensile strength: 2210 MPa; Young modulus 143 GPa).

Glue
For both IPC TRC and CFRP a commercially available epoxy glue is applied [11].

3. RESULTS AND DISCUSSION

3.1 Influence of the pre-treatment

The 4 beam types designed to investigate the influence of a pre-treatment (first series in Table 1) all fail by debonding of the external reinforcement at a mixed flexural and shear crack. The beams which have undergone a pre-treatment debond interlaminar in the IPC TRC, while the beams without any pre-treatment debond in the laitance layer of the concrete. These failure locations indicate that the concrete laitance is effectively the weakest link in the connection between the concrete substrate and the external reinforcement. By removing this weak layer the failure location changes to the IPC TRC.

Figure 2 compares the load-deflection curves of all pre-treatment types. A comparison indicates no significant difference in the loadbearing behaviour, including the failure load, of the beams with different pre-treatments. This means that the roughness of the concrete substrate has no influence on the overall loadbearing behaviour. The only exception is the beam where no pre-treatment is applied, which loses the initial high stiffness at a lower load (± 6 kN) than its pre-treated counterparts (± 7 kN), which is probably due to the fact that the weak laitance layer is still present.

![Figure 2](image_url)

Figure 2. There are no significant differences in the loadbearing and failure behaviour of the different plain pre-treated beam types, only the one without pre-treatment exhibits an earlier loss of the initial high stiffness and failure within the concrete laitance.

3.2 Influence of the contact width

The influence of the contact width is studied based on the second specimen series in Table 1. Two pairs of full and half-covered alternatives, each with the same reinforcement cross-section (I4-F-DS and I8-H-DS; I6-F-DS and I12-H-DS) are compared.

The maximum load taken by the beams fully covered by IPC TRC is higher than the maximum load carried by the beams with the same section of external reinforcement but covering only half of the concrete surface area (4 vs 8 layers: 40 %; 6 vs 12 layers: 76 % – Figure 3). This phenomenon is linked to the different failure modes: the fully covered beams fail due to a tensile failure of the external IPC TRC right underneath a flexural crack, while the half covered alternatives first exhibit interlaminar debonding in the IPC TRC, starting at a flexural crack and ending with a tensile IPC TRC failure. This difference in failure mode can be explained by the fact that for a same total load the same forces have to be transferred between the concrete and the external IPC TRC. For the fully covered beams the area over which these forces can be transmitted is twice the one of the only half covered beams, resulting in lower stresses for the same external load and thus in a more favourable failure mode. This explanation is directly linked to the reasoning behind the larger amount of cracks for the fully covered beams, discussed in the following paragraph.

Based on the DIC results, Figure 4 shows the relative horizontal displacement (Y-axis) versus the horizontal position on the beam (X-axis) for different load steps at a height of about 3 mm in the concrete. The cracks are marked with a number above the graph. A crack is defined at the maximum load as a difference in horizontal displacement larger than 0.02 mm over a horizontal interval of 5 mm, which is not adjacent to another crack interval. An overview, based on the longitudinal strain field, of the identified cracks and their numbering is given in the top left corner of each beam type. The amount of cracks is more or less doubled (7/8 instead of 4) when the contact area is doubled. For this relatively small variation in cross section, this observation seems to be independent of the amount of reinforcement, indicating that the number of cracks only depends on the contact area between the concrete and the IPC TRC.
Figure 3. Load-deflection curves indicate that covering the full concrete area increases the ultimate load, also resulting in a more ductile and favourable failure mode.

Figure 4. Covering the full concrete bottom surface with IPC TRC results in the double amount of cracks (7 to 8) compared the only half-covered alternatives (4).

Figure 5. Considerably smaller crack widths are obtained for the fully covered beams compared to their only half-covered alternatives.

To study the individual crack width evolution in more detail, Figure 5 plots the load versus crack width for all identified cracks in Figure 4. The plots show that for a given load step the cracks open less wide for the fully-covered beams (left) compared to their half-covered alternatives (right). The widest crack, which is the determinant one concerning the serviceability limit state, reaches at the last comparable load step of 6 kN only 5 µm width for I4-F-DS (crack 7) versus 10 µm for I8-H-DS (crack 1), and 5 µm for I6-F-DS (crack 5) versus 13 µm for I12-H-DS (crack 4). These smaller crack widths are directly linked to 2 phenomena observed in Figure 4: (i) the greater amount of cracks, and (ii) the lower total horizontal displacement. The higher the number of cracks, the lower the crack width becomes for each individual crack in case the total horizontal displacement is equal. This total horizontal displacement shows however to be even significantly smaller at the last comparable load step for the beams where the full concrete area is covered than for the beams where only half of the area is covered (I4-F-DS: 0.029 mm vs I8-H-DS: 0.037 mm at 6 kN; I6-F-DS: 0.052 mm vs I12-H-DS: 0.108 mm at 7 kN). This means that the smaller crack widths are not only due to a higher amount of cracks, but that their opening is even further prohibited.

This limitation of the crack opening can probably be attributed to the crack bridging capacity of the external IPC TRC reinforcement. Figure 6 illustrates this crack bridging capacity by the fact that the localized apparent stains in the concrete (framed in white), corresponding to cracks, are spread over a much larger area in the IPC TRC reinforcement. For the fully covered beams this crack bridging is more efficient as the contact area, and thus the concrete volume influenced by this crack bridging, is twice as high.
3.3 IPC TRC versus FRP

Some similarities exist in the load-deflection behaviour of the I8-F beams (I8-F-DS is chosen as representative) and the CFRP reinforced alternatives (series 3 in Table 1) enabling a comparison between them (Figure 7). They all exhibit a similar initial stiffness and the I8-F-DS and C-14-DS obtain a comparable maximum load. The beam externally reinforced with the 14 mm wide CFRP strip (C-14-DS) fails at a load of 10.6 kN by premature debonding of the external reinforcement at a mixed flexural and shear crack. In contrast to the IPC TRC reinforcement this delamination takes place within the concrete substrate, indicating the shift of the weakest location: the reinforcement for the IPC TRC and the concrete for the CFRP. Increasing the cross section of the CFRP reinforcement strip results in an increase in ultimate load (40 mm: 15.7 kN; full width: 22.1 kN). Also the failure mode evolves from debonding of the external reinforcement at a mixed flexural and shear crack to a pure shear failure, as indicated in Figure 7.

Similar to Figures 4 and 5, Figures 8 and 9 represent the cracking evolution based on the DIC results. Mutual comparison of the CFRP-reinforced beams indicates that the beam externally reinforced with the 14 mm wide strip is the only one that forms only 3 cracks at failure load. Both other specimen types exhibit 6 cracks. However, 8 minor strain concentrations form for beam C-F-DS. This could indicate that if failure was not occurring by shear, additional cracks could have developed further resulting in a higher total amount of cracks compared to the beams reinforced with smaller CFRP widths (14 mm: 3 cracks; 40 mm: 6 cracks; full: 6 + 8 cracks). Assuming the latter, these conclusions correspond to the ones for IPC TRC, namely that the number of cracks at the ultimate load increases with an increasing contact width. Apart from the growing number of cracks, the total crack width at a comparable load step reduces for an increasing CFRP reinforcement cross section. This can easily be explained by the larger beam stiffness as a result of the larger reinforcement area. Comparison of beams I8-F-DS and C-14-DS, which fail at approximately the same load, shows that the application of IPC TRC over the entire tensioned bottom surface results in double the amount of cracks (6 vs 3) and in a significantly smaller total crack opening (1.0 mm versus 1.4 mm). This observation is in line with the findings on the individual materials: being that the number of cracks increases with an increasing contact width between the external reinforcement and the concrete.

4. CONCLUSION

This experimental campaign with 32 specimens of 11 different specimen types indicates the great possibilities of external TRC and FRP reinforcement, especially with regard to the cracking behaviour of the underlying concrete substrate. This paper indicates that a pre-treatment of the concrete substrate prior to the application of the external reinforcement is necessary, but that the type of pre-treatment does not influence the loadbearing or failure behaviour. Additionally the importance of a large contact area between the external reinforcement and the concrete is illustrated. A larger contact area results in a higher failure load, a more preferable failure mode, a larger amount of cracks in the concrete substrate and as a result smaller individual crack widths. All these beneficial aspects can be explained by the crack bridging capacity of the external reinforcement, which has a larger influence for a larger contact area. The differences and mainly the advantages of TRC over FRP reinforcement can be mainly attributed to this phenomenon: due to a smaller strength and stiffness of the TRC a larger reinforcement cross-section is needed, often resulting in a larger
contact area. This lower strength also results in the shift of the failure location in case of debonding from the concrete substrate to interlaminar in the TRC.

Figure 8. A larger CFRP contact width with a plain concrete beam and reinforcement area result in an increasing number of cracks, with a lower total crack opening.

Figure 9. The individual crack opening decreases with increasing CFRP reinforcement area and contact width with a plain concrete beam.

REFERENCES