BENDING OF BEAMS EXTERNALLY REINFORCED WITH TRC AND CFRP MONITORED BY DIC AND AE

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ABSTRACT

Strengthening and repairing existing reinforced concrete structures is often more economical and sustainable than rebuilding them. The most commonly used technique, externally bonded Carbon Fibre Reinforced Polymers (CFRP), does not answer the need for a temperature resistant, fire safe and economical solution. High performance glass fibre Textile Reinforced Cements (TRC) can offer an answer to these drawbacks. A validation of this TRC technique against the existing one of CFRP is still needed. The Digital Image Correlation (DIC) and Acoustic Emission (AE) measuring techniques are applied to monitor the bending, cracking and failure behaviour of a reference beam, a beam with CFRP external reinforcement and a pr-cracked and non-pr-cracked TRC external reinforced beam. Four-point bending tests indicate the successful complementary use of DIC and AE and prove that TRC as an external reinforcement for concrete beams actually works.

1 INTRODUCTION

The growing urbanization together with the awareness on reducing carbon emission originating from construction industry, increases the need for strengthening and repair of existing buildings and infrastructure, in disfavour of new construction. The most commonly used technique to strengthen steel reinforced concrete structures is currently the application of externally bonded Fibre Reinforced Polymers (FRP). For this application most often carbon fibres are embedded in an epoxy matrix (CFRP). [1, 2]

The use of composites with a cement matrix for the strengthening of concrete structures has however some advantages in comparison with the existing techniques, in particular the material’s resistance against fire and high temperatures. Recent progress in the field of cement composites has led to the development of high performance Textile Reinforced Cements (TRC), which have a sufficiently high tension hardening capacity to be applied for the strengthening and repair of concrete structures. The use of a continuous fibre reinforcement instead of discontinuous fibres makes it possible to control the fibre distribution and align the fibres along the principal stress direction. Using adapted production techniques, such as hand lay-up or pultrusion, high fibre volume fractions of up to 25 % can be achieved, leading to a tensile strength of up to 60 MPa [3, 4].

In order to evaluate the potential of TRC as an alternative external reinforcement to FRP’s, the mechanical behaviour of reinforced concrete beams strengthened by these different
external reinforcement materials should be accurately characterised. Therefore, complementary to the measurement of the standard parameters like load and deflection, the non-destructive testing (NDT) techniques Digital Image Correlation (DIC) and Acoustic Emission (AE) were applied to monitor the bending behaviour and crack pattern of externally reinforced beams.

AE utilizes piezoelectric sensors to detect the elastic waves emitted by crack propagation incidents. It is used to determine the onset of fracture and follow its development [5]. Analysis of waveform parameters helps in characterizing the fracture mode and intensity.

DIC visualizes 3D displacement fields, and as a consequence strain fields, by comparing subsequent pictures taken of a speckle pattern on the surfaces of the beams [6]. As cracks are characterized by discontinuities in the displacement field, DIC is a good measuring tool to analyze fracture evolution and failure modes.

This paper discusses four-point bending tests with third-point loading performed on four different types of concrete beams. It compares the load-deflection and cracking behaviour of a reference beam, a beam with CFRP external reinforcement and a precracked and non-precracked TRC external reinforced beam. To do so, the outcome of DIC and AE measurements are analysed. Both NDT techniques are expected to act complementarily in order to cover their weaknesses and improve their advantages as will be analysed below [7].

2 TEXTILE REINFORCED CEMENTS

Cementitious materials are stiff and strong materials in compression, but they are characterized by a low tensile strength and a brittle behaviour. Therefore these materials need to be reinforced with traditional steel reinforcement or, alternatively, with fibres. Until now most studies concerning fibre reinforcement for concrete concentrated on discontinuous fibre structures, which can increase the ductility but hardly or not the tensile strength [8]. To create a ductile cement matrix composite with an increased tensile strength, a dense and continuous fibre structure such as fibre textiles should be used, leading to a Textile Reinforced Cement (TRC). The production techniques as well as the mechanical properties of TRC are closer to the ones of polymer matrix composites than to those of more common cement composites with discontinuous fibre structures: with techniques like tape winding, pultrusion or calendaring it is possible to control the alignment of the fibres and to achieve TRC’s with a high fibre content (up to 25 % in volume [3]). This leads to a stable crack development and a strain hardening behaviour with a significant post-cracking stiffness and a high tensile strength. The small diameter of the fibres results moreover in a very fine crack pattern [9].

Cost effective E-glass fibres are often used in the composites industry. An important drawback however of these fibres in combination with a cementitious matrix is the reduction of their performance with time due to the alkaline environment of an ordinary concrete or mortar [10] and to portlandite deposition. In order to avoid fibre degradation the Vrije Universiteit Brussel developed an Inorganic Phosphate Cement (IPC), which is acidic in fresh state, but neutral after hardening. The time of the acidic phase is sufficiently short not to degrade the properties of the glass fibres. Its relatively small grain size (between 10 and 100 µm) moreover enables to impregnate dense textiles up to high fibre volume fractions (up to 25 % in volume [3]). As a result, a durable cementitious composite with high tensile (up to 60 MPa for IPC reinforced with randomly oriented glass fibre textiles) and compressive (80
MPa) capacities and which is heat- and fire resistant (highest European class A1), is created, what makes it appropriate for structural applications.

Under compressive stress states, the constitutive behaviour of glass fibre textile reinforced IPC can be assumed to be linear elastic until failure of the matrix (80 MPa [11]). Under tensile stresses, on the contrary, it shows a complex and non-linear stress-strain evolution (Figure 1).

![Figure 1: The tensile stress-strain behaviour of IPC reinforced with glass fibres randomly oriented in a plane is nonlinear](image)

Three stages (I, II and III in Figure 1) can be distinguished in the IPC tensile behaviour. The initial behaviour in stage I is linear elastic, and fibres and matrix can be assumed to work perfectly together. Since the tensile failure strain of the matrix is low, cracks will occur at low stresses and strains. When sufficient fibres are present to take over the load at the crack location, multiple cracking will occur in this second stage. It can be noticed from Figure 1 that crack formation is a nonlinear and gradual process. Once the matrix is fully cracked, only the fibres will contribute to the tensile strength and stiffness of the material (stage III), until the fibres fail.

Glass fibre textile reinforced IPC can be classified as a High Performance Fibre Reinforced Cement Composite (HPFRCC), as it fulfils the requirements specified in [12]. The main requirements imply: multiple cracking behaviour with crack width control, strain hardening behaviour and a high tensile strength. Following this classification this material will be referred to as HPFRCC IPC.

3 DIGITAL IMAGE CORRELATION

Digital Image Correlation (DIC) is an optical, non-contacting measuring technique, enabling the possibility to determine the displacement- and deformation field of the specimen’s surface under any type of loading condition. Prior to testing a speckle pattern of black spots on a white background is applied on the specimen’s surface. Out of grey scale pictures taken during testing by two CCD cameras of this speckle pattern, a 3D image can be created. The measurements are based on the comparison of a reference image, generally in the unloaded stage, with the images taken at the different load steps. The comparison is done by searching for the same group of neighbouring pixels (called a subset) in both the reference and the loaded images. This comparison results in the displacement, represented in the centre of the subset. By moving the centre point of this subset over the whole image, in steps of a certain amount of pixels (called the stepsizer), the full displacement field can be calculated.
Out of a square grid of displacement points (called a strain window), the strain can be derived and represented in the centre of the strain window. Again by repetition the whole strain field can be obtained. [6]

The DIC technique is a valuable and promising tool to identify and quantify the crack pattern of concrete beams with externally bonded reinforcement, as cracks cause a discontinuity in the displacement and strain field, which is measured by DIC.

4 ACOUSTIC EMISSION

The AE technique measures the stress waves emitted by propagation of cracks. The AE signals (hits) are recorded by transducers mounted on the material. The source of these waves is an “event” (for example, one crack nucleation or propagation incident). One event leads to a pulse opening as a spherical wave front, and is recorded by piezoelectric sensors attached at different places on the surface. Analysis of the recorded electric waveforms can provide useful information about the internal condition of the structure. The advantage of AE is the recording of the damage process from the onset of fracture and tracking of all subsequent failure stages. So far, AE parameters like frequency and signal duration have shown sensitivity to the failure modes [13], and have been used for monitoring the damage evolution under bending tests [14], compression [15] or pullout [16]. Specific AE indexes have been used to identify the moment of critical failures [17, 18] much earlier than visual observation or drop of mechanical load readings. Therefore, AE is also applied in the monitoring of full-scale structures [19, 20].

5 TEST SET-UP

A four point bending test with third point load is performed on reinforced concrete beams with a total length of 2.5 m, a distance between the supports of 2.3 m, and a height and width of 0.3 m and 0.2 m. The loading is displacement controlled using a servo-hydraulic actuator with an initial displacement rate of 0.2 mm/min. After the cracking moment is clearly surpassed (load of 60 kN), the displacement rate is increased to 2 mm/min. The test set-up is illustrated in Figure 2.

![Figure 2: A four point bending test with third point load is performed on the external reinforced beams](image)

Four different beam types are tested. The first type, a HPFRCC IPC strengthened beam, is a reinforced concrete beam that is externally strengthened by gluing a strip made of IPC reinforced with 16 glass fibre mat layers (resulting in a nominal thickness of 8 mm) over the entire tensioned lower surface of the beam. To simulate actual loading conditions a second beam type is tested where the reinforced concrete is precracked before it is repaired with the
same amount of externally bonded HPFRCC IPC. To enable comparison of TRC with CFRP as external reinforcement material, the third beam type is a CFRP strengthened beam, for which a CFRP strip with a standard thickness of 1.2 mm is installed underneath the concrete. The width of the strip is 30 mm, so as to obtain the same ultimate load as the HPFRCC IPC reinforced beam, following the FIB bulletin 14 [1]. The fourth beam type is a reference beam without external reinforcement. In all the cases the external reinforcement is glued onto the concrete using a two-component epoxy glue (PC 5800/BL [21]). Before attaching the reinforcement to the beams, the concrete surface is pretreated to remove the laitance layer. All beams have an internal steel reinforcement, consisting of two longitudinal bars with a diameter of 16 mm and stirrups with a diameter of 6 mm placed every 100 mm in the shear zones of the beams. This shear reinforcement is overdimensioned in order to have the final failure in bending in the zone of constant moment. The reinforcement bars are welded to steel plates at the end of the beams; this eases the positioning and placing of the rebars and eliminates potential problems with the anchoring length of the reinforcement bars. The stirrups are welded to the longitudinal bars as well.

For the crack pattern measurement a pair of DIC cameras follows the side edge of the beam. This system is able to measure an approximately 0.4 m wide area at the centre of the beam, corresponding to the constant moment area (Figure 3). Pictures are captured every 0.2 kN and every 5 seconds. The analysis is done using the VIC3D-2009 software package from Correlated Solutions where a subset size of 21 pixels, a step size of 5 pixels and a strain window size of 11 are used.

![Figure 3: A DIC camera system monitors the beams](image)

Concerning AE, in total eight sensors were applied on the central part of the span. Five sensors were placed at the side and three at the top surface, as shown in Figure 4. Two types of sensors were used, namely the resonant, sensitive R15 and the broadband WD of Physical Acoustics Corp. (PAC). Signals exceeding 35 dB were digitized and stored in a PAC micro-II 8 channel system.

![Figure 4: Photograph of the IPC reinforced beam with AE sensors. The sensors on the side were supported by magnetic clamping devices.](image)
6 USED MATERIALS

6.1 Concrete

The concrete material characteristics are described in Table 1. The values are the mean values of 8 test specimens for the compressive strength and 3 for the modulus of rupture. These material characteristics are experimentally determined after 48 days. The compressive strength given in Table 1 is the cylindrical strength calculated from tests performed on cubic shaped specimens, with sides of 150 mm. The young modulus can be calculated from the compressive strength. All calculations are based on [22, 23].

Table 1: The material properties of concrete

<table>
<thead>
<tr>
<th>Compressive strength (MPa)</th>
<th>35.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus (GPa)</td>
<td>34.0</td>
</tr>
<tr>
<td>Modulus of rupture (MPa)</td>
<td>5.3</td>
</tr>
</tbody>
</table>

6.2 HPFRCC IPC

The matrix material IPC is mixed in the mass proportions of:
- 1 vubonite liquid component
- 0.82 high performance vubonite powder

The IPC matrix is reinforced with 16 randomly in-plane oriented fibre textiles, being chopped strand mats Vetrotex M5, with a surface density of 300 g/m², resulting in a fibre volume fraction of 21%. The material characteristics of HPFRCC IPC reinforcement are described in Table 2. The values are the mean values of 10 specimens.

Table 2: The material properties of HPFRCC IPC

<table>
<thead>
<tr>
<th>Tensile strength (MPa)</th>
<th>58.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate strain (%)</td>
<td>1.2</td>
</tr>
<tr>
<td>Young modulus stage I (GPa)</td>
<td>12.5</td>
</tr>
<tr>
<td>Young modulus stage III (GPa)</td>
<td>4.8</td>
</tr>
</tbody>
</table>

6.3 CFRP

Only one tensile test is performed on a CFRP strip, resulting in a tensile strength of 2210 MPa and a Youngs modulus of 143 GPa.

6.4 Steel reinforcement

The traditional steel reinforcement consists of ribbed bars made of S500 steel, of which the material characteristics were not experimentally derived, so the standard values of 500 MPa for the yield stress and 200 GPa for the young modulus are assumed.

7 EXPERIMENTAL RESULTS

7.1 Load-deflection curves
The HPFRCC IPC beams exhibit a similar load-deflection behaviour, while the strength is clearly higher than the CFRP reinforced and the reference beam.

The comparison of the load-deflection curves of all four beam types yields findings on two subjects. First, it allows us to evaluate the influence of pre-cracking on the efficiency of the external TRC reinforcement. Secondly, it assesses the potential of TRC as an alternative to CFRP external reinforcement.

As the load-deflection curves (Figure 5) show, precracking the beam does not influence the overall behaviour of the HPFRCC IPC beams. This indicates that the repair method actually works and is not influenced by the history of the concrete structure.

As comparison of the HPFRCC IPC beams with the CFRP and reference beams shows, the HPFRCC IPC beams retain their stiffness significantly longer (± 50 kN instead of ± 30 kN or an increase of 67 %). This raise in cracking bending moment causes an upward shift of the second part of the curve, resulting in a lower deflection for the same applied load. This shift may be useful in cases where the serviceability limit state of deflection is governing.

Finally, the ultimate load of the HPFRCC IPC reinforced beams (210 kN) is higher than the one of the CFRP reinforced beam (190 kN). This 10 % lower strength of the CFRP reinforced beam is caused by the early local debonding of the CFRP strip, which is due to the smaller contact area, before the full tensile failure of the strip.

The differences between the HPFRCC IPC reinforced beams and the CFRP reinforced beam may be explained by the bigger contact area of the HPFRCC IPC reinforcement, which not only enables a better bond, avoiding peeling-off, but also precludes better the crack extension and opening. This reasoning will be verified with the DIC results in “7.2 Results by DIC”.

### 7.2 Results by DIC

In this section, the DIC-images are interpreted to yield the crack pattern and its evolution for the different beam types. In this way, any difference in cracking behaviour between the TRC and CFRP reinforced beams is visualised.

Figure 6 shows the horizontal displacement (Y-axis) versus the horizontal position on the beam (X-axis), both expressed in mm, for different load steps. The curves are obtained by
extracting the DIC data over a full line with 2000 points, drawn over the entire visible width, as close as possible to the bottom but still in the concrete area. The vertical discontinuities indicate a sudden increase in displacement, and thus a crack in the concrete.

An overview of the plotted cracks and their numbering is given in the top left corner of each graph. This overview is based on the strain field of the beam at its maximum load, except for the reference beam where it is taken at 140 kN. The purple colour represents a negative or zero strain field, and the more the colour evolves to red tones the higher the strain becomes. The red zones, representing a strain of 1% or higher, indicate the cracks.

![Graphs showing crack patterns](image)

Figure 6: The HPFRCC IPC reinforced beams show more cracks, which grow less wide than the CFRP reinforced and the reference beams

Due to a too large displacement of the reference beam the pictures of the last load steps (from 140kN onward) cannot be correlated correctly and so no reliable results can be retrieved.

As comparison of the non-strengthened with the externally reinforced beams in Figure 6 shows, adding reinforcement increases the number of cracks: two for the reference beam, three for the CFRP beam and seven for both the HPFRCC IPC reinforced beams. Even though the externally reinforced beams are designed to fail at the same load, their cracking pattern is considerably different. The HPFRCC IPC reinforced beams have more than double the amount of cracks with more or less the same total displacement at the same load. This results in a lower crack width for each crack, which can influence favourably moisture penetration and thus durability of the inner steel reinforcement. This difference is probably due to the bigger contact area of the HPFRCC IPC reinforcement.
The evolution of the crack widths with an increasing load is given in Figure 7. All cracks present in the beams are represented and indicated with the same numbering as in Figure 6. To clarify the onset of the crack development, the bottom right corner shows a zoom in this curve for loads from 0 kN to 80 kN and crack widths from 0 mm to 0.05 mm. In all graphs the relapse of the curve after the maximum load is reached, is left out to preserve the overview.

Figure 7: Even though the initial stiffness is preserved, the first cracks occur for all beams at a load of about 20 kN.

Figure 7 indicates that all beam types exhibit already at least one crack at a load of about 20 kN, even when the initial high stiffness does not reduce till a higher load. This leads to the conclusion that the raise in cracking moment in Figure 5 is only an apparent retardation, as the stiffness is retained but the cracks actually initiate. These graphs confirm the conclusions from Figure 6, that the HPFRCC IPC reinforced beams have more than double the amount of cracks, resulting in a lower crack width for each crack.

7.3 Results by AE

AE is quite suitable to detect the onset of cracking due to the early emission detected by the sensors. This is an important part of the study since one of the targets of reinforcing with an external layer, is to delay cracking. This has a positive influence on the structural condition because surface cracking allows the ingress of environmental agents which accelerate corrosion and degradation. Since the ambient noise was low enough, the onset of cracking is considered to be the first acoustic emission signal that was recorded.
Figure 8 shows the early AE activity in terms of the cumulative number of recorded hits as a function of load for the different beams. It is seen that the accumulation of events starts for the reference beam first (specifically at the load of 4.8 kN), while the overall behaviour of the CFRP reinforced beam (starts at 8.6 kN) is quite similar. The HPFRCC IPC reinforced beam is the only one where AE started above 10 kN (specifically 11.3 kN). From the cumulative activity it is obvious that the two beams reinforced with HPFRCC IPC exhibit much delayed activity which is connected to the conservation of stiffness. At the load of 15 kN, the reference and CFRP reinforced beams had already accumulated the AE activity that the HPFRCC IPC exhibited at 30 kN. These observations confirm the ones of Figure 7, obtained by DIC.

Apart from the number of AE recordings, valuable information can be sought for in the AE waveform parameters. Figure 9a shows the average frequency (AF) of hits recorded by the broadband sensors as a function of time, along with the load history for the HPFRCC IPC reinforced beam. The solid line is the moving average of the recent 100 hits. While the data are well dispersed on different frequency levels, the average line shows some specific fluctuations at moments denoted by numbers in the graph. At point 1 the AF line decreases by more than 30 kHz, while at the same moment a drop is also noted in the load line. At point 2 there is a smaller drop of frequency which coincides with the maximum load sustained by the beam. At the rest of the points (3 and 4), temporary decreases of AF occur simultaneously with load drops. Figure 9b shows the corresponding information for the duration of AE signals. At the same moments as in Figure 9a, similar fluctuations are noted but with the inverse trend (increasing). This shows that noticeable changes take place during the different fracturing stages of the beam and in conjunction with the DIC strain patterns it is possible to assign specific damage mechanisms to their AE signature.
8 CONCLUSIONS

The complimentary use of NDT techniques proves very useful for the characterization of the mechanical performance of the beams. AE accurately determines the onset of cracking and monitors the development of fracture in the whole gauge volume while DIC supplies quantitative information about the actual strain field at the specimen surface. Results show clearly the retarding effect that the externally bonded HPFRCC IPC has on the cracking of the concrete beam. DIC confirms the distribution of fracturing incidents in a wider area due to the larger number of developing cracks with smaller width, compared to the reference beam. Furthermore, AE clearly shows that the cracking is very much restrained for the HPFRCC IPC reinforced beams since the activity for loads up to 30 kN is negligible. The beneficial character of HPFRCC IPC external reinforcement on crack restraining is reflected on the macroscopical mechanical properties of the beam, since the HPFRCC IPC beams exhibited a 10% higher maximum load than the CFRP reinforced beams, and 35% than the reference beam with only the traditional metal rebars.

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