Monitoring of the Structural Behaviour of Hybrid Composite-Concrete Beams by Means of Acoustic Emission and Digital Image Correlation

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Abstract. Textile Reinforced Cements (TRC) and Fibre Reinforced Polymers (FRP) allow the development of lightweight components. The lightweight design examined herein for structural applications consists of prefabricated TRC hollow beams with FRP reinforcement, on which a concrete layer is cast. Before however, such designs find their way to application, their load bearing capacity and failure mechanisms should be fully understood. The beams were tested in four-point bending while the basic design was slightly changed in terms of the amount of carbon FRP and concrete layer thickness. During loading two monitoring non-destructive testing (NDT) techniques were applied: Acoustic Emission (AE) and Digital Image Correlation (DIC). The characteristics of AE waveforms were analysed and correlated to the active fracture mechanisms including TRC and concrete cracking, as well as debonding between the successive TRC layers and delamination of the carbon strip. DIC is used to measure the real time strain fields on the surface enabling the visualization of the stress concentration points. The two techniques work complimentary in that DIC supplies accurate strain development and damage localization on the surface while AE collecting emissions from all the volume of the beam indicates the load of the failure onset and enlightens the fracture mechanisms. This is one of the first studies where essential combination of the two NDT techniques is applied for monitoring of these innovative hybrid structural elements.

Introduction

Composites in construction are continuously gaining ground due to their high strength-to-weight ratio and their good corrosion properties compared to the traditional concrete elements. “Hybrid” designs aim to combine the high compressive resistance of concrete with the high elastic modulus of fibre reinforced polymers (FRPs) [1, 2]. However, these FRPs do not exhibit strong fire resistance. An answer to this issue is offered by the low-cost textile reinforced cements (TRCs) [3]. Vrije Universiteit Brussel (VUB) developed an inorganic phosphate cement (IPC) [4], which is combined with dense glass fibre textiles, resulting in a high performant TRC with fibre volume fractions of up to 25%. This material offers many advantages as it allows building lightweight structures with excellent fire behaviour. However, the mechanical and fracture properties of the resultant components should be investigated due to the heterogeneity and complexity of the materials and the
design. In this paper two different beam designs are tested in bending and compared. One beam type is a TRC hollow box that consists of an IPC matrix and approximately 20 volume % of glass fibres in random orientation in the form of fibre textiles. The other type consists of a similar TRC tube but carries a layer of concrete on top and a CFRP strip attached to the outer bottom surface of the hollow TRC beam (see Fig. 1). The test is accompanied by acoustic emission (AE) monitoring. Apart from the mechanical results of the different types of beams, the main aim of this paper is to check if AE can follow the fracture process in composite construction elements. The mechanisms of failure in TRC include cracking of the brittle matrix at relatively low loads and later delaminations between successive fibre layers as well as fibre pull-out. For the hybrid design, on top of these possibilities, there may be debonding incidents between the concrete and the TRC box as well as debonding of the CFRP strip. These additional mechanisms are triggered directly by shear forces and thus, when failure occurs, they are expected to lead to differences in the emitted elastic waves captured by AE. This paper is a continuation of a research effort to build a methodology based on Digital Image Correlation (DIC) and AE for monitoring the mechanical behaviour of lightweight hybrid composite elements for construction [5].

**Fig. 1.** Cross section of the hybrid beams (left) and the plain TRC beams (right).

### 2. Experimental details

#### 2.1 Materials

For the plain TRC beams, the hollow box is obtained by impregnating four 2D random glass fibre textiles (300 g/m²) with the IPC cementitious matrix. For the hybrid beams on the other hand, the TRC hollow box is produced with eight instead of four of these glass fibre textiles. For both beam types, this results in a fibre volume fraction of about 20 % and an average tensile strength of 44 MPa. For the hybrid cross section this TRC box is finished with a gravel layer (max. 4 mm) to enhance the connection between the box and the concrete compression layer.

The concrete is mixed in following mass proportions: 380 kg Portland cement CEM I 52.5N; 152 l water; 482 kg sand (0/2); 1378 kg gravel (4/7). After 28 days this concrete compression layer obtained an average compression strength of 36.4 MPa, measured on four prismatic specimens and afterwards converted into the standard cylindrical strength.

The CFRP strip is a commercially available strip [6], with a tensile strength greater than 2850 MPa and a stiffness greater than 175 GPa (according to the supplier).
2.2 AE monitoring

Monitoring by AE sensors allows recording of all transient waves emitted by the damage propagation events [7]. On top of that, the different damage mechanisms induce a different crack tip motion resulting in quite different AE characteristics. This enables passive monitoring and characterization of the dominant fracture mode [8, 9]. The information of AE concerns the location of the sources, the amount of activity - which is related to the number of active sources - and the characterization of the dominant fracture mode. The number of AE signals in relation to the load also supplies important information which, in some cases, may be the most serious criterion in a health monitoring scheme [10]. Additional information about the fracture mode can be supplied by analysis of AE waveform parameters. High frequency content of the waveforms are indicative for a tensile mechanism, while signals with long duration and rise time (RT) (see Fig. 2) indicate shearing as has been seen in composites, concrete and granite [11-13]. This is of particular importance in composites and complex materials, as the fracture process is not straightforward and the load-deflection curves are not enough to provide information on the mechanisms of fracture.

![Fig. 2. Schematic representation of an AE waveform with some basic parameters. Average frequency AF is calculated by the number of threshold crossings over the duration.](image1)

![Fig. 3. Photograph of the hybrid beam before test. The two horizontal arrays of sensors are covered by tape.](image2)

Two arrays of sensors were attached along the hybrid beams (see example of Fig. 3). Sensors 1,3,5,7 were attached on the concrete layer (top) while 2,4,6,8 on the TRC box (bottom). In the previous approach only one array was used on the concrete [5]. The horizontal distance between successive sensors was 23 cm and the whole area covered 70 cm in the centre of the beam. Linear location was enabled for the two groups of sensors (one on concrete and one on TRC). The analysis below concerns all activity (hits) registered in “events” meaning that they were received by sensors within a limited window of time and their source was located in the gauge area. For the plain TRC beams, both arrays were placed on the TRC box. Therefore, for the comparison below only the activity received by the sensors on TRC is considered.

2.3 Digital image correlation

Full field displacement- and consequently deformation- and strain fields can be obtained by digital image correlation (DIC). The full field measurements are the result of a comparison of subsequent surface pictures of the specimen at different load steps. These grey scale pictures are taken by two charged coupled device cameras of a speckle pattern (different
black dots on a white background) that is applied on the specimen. The use of two cameras results in a three dimensional measurement. [14]

For this specific test series the speckle pattern is applied on the hybrid beams using the silk screen printing technique. Two 3D DIC systems are used to monitor one half of the beams: a first system following an approximately 550 mm wide area starting from the middle of the beam (DIC 1 in Figure 4) and a second system focused on the outer 950 mm of the beam’s span (DIC 2 in Figure 4).

![Figure 4](image)

Fig. 4 Half of the beam is monitored by two 3D DIC systems.

3. Mechanical results

Fig. 5 represents the load-deflection curves of the simple TRC hollow box in blue and the full hybrid beam in red. Considering the correspondence between both beams of each beam type, only one beam per type is represented in Fig. 5. The load is measured by a load cell and the deflection by an LVDT positioned beneath the centre of the beam’s span. Both the stiffness as well as the ultimate load of the hybrid beam (22.4 kN) are considerably higher than the ones of only the box (0.7 kN). These differences are due to several reasons: (i) the additional concrete compression layer, (ii) the presence of a CFRP reinforcement strip and (iii) the double thickness of the TRC box. Similar differences were observed between hybrid beams with and without additional CFRP reinforcement [5].

![Figure 5](image)

Fig. 5 The simple box clearly exhibits a less stiff and strong behaviour than the hybrid beam.

For both beam types the applied load steadily increases until a sudden failure. Afterwards inspections revealed that the hollow TRC boxes failed in compression of the TRC
underneath one of the two point loads (bottom picture in Fig. 5) while the hybrid beams failed by debonding of the external CFRP strip (top picture in Fig. 5).

4. AE results

It should be mentioned that in the framework of this study two types of beam designs are discussed out of several other tested designs. For reasons of consistency with future complete studies we will keep their original reference number; #5 and #6 for the hybrid and #9 and #10 for the TRC boxes.

Expressing AE activity as a number of hits or events is quite common. Moreover, it is well known that this AE activity is correlated to the rate of cracking and the number of active sources. Since this manuscript focuses on the possibility to characterize the different damage mechanisms, the AE values of different parameters (such as RT, AF) are used instead of the cumulative numbers of events.

The full period of the experiment was divided in eleven steps from start to finish. Stage #1 refers to the lowest load. The activity recorded during this stage can be due to preliminary activation of the failure mechanisms. Stage #10 concerned the activity at the peak load, while stage 11 was recorded after the load drop while the deflection was still increasing (see Fig. 6).

![Fig. 6. Load in kN (parametric 2) vs. time for the hollow TRC box. The load values are negative due to the downward movement of the load cell. Each point in the plot is an AE hit showing the corresponding time and the load when it was recorded.](image)

For these 11 stages the values of the AE parameters are averaged and presented in Figs. 7 and 8. Fig. 7 includes the data for the hollow IPC boxes (namely Beam #9 and Beam #10 in our experiment). It is typical for these beams that the values for the pre-peak stages #1-9 of both beams are all contained in a small window of high average frequency (>110 kHz) and low rise time (< 45 μs). Such AE signals correspond to the tensile cracking of the brittle IPC matrix that already starts at low loads. Moreover, this fracture mechanism remains the same for all load stages until approximately 80% of the ultimate load. This mechanism is reasonably the tensile cracking of the brittle IPC matrix that already starts at low loads. At the peak stage the points are pushed out of this box extending to longer RT, meaning that shearing starts to become more active just before and during the peak load. Shearing can happen between the successive glass fibre layers within the TRC as well as by the pull-out
of fibres which are bridging the cracks in the IPC matrix. Finally at stage 11 the points reach much lower frequencies (40-70 kHz) and longer RT since after the macroscopic collapse of the beams, the cracking at the fractured areas is (almost) saturated while the pull out of fibres and delaminations continue as the deflection goes on.

Fig. 7. Average frequency vs. rise time for two full TRC beams.

Fig. 8. Average frequency vs. rise time for two hybrid TRC-concrete beams.

The situation is distinctly different for the hybrid beams 5 and 6 in Fig. 8. During the initial stages of loading, the emitted signals are located outside the defined window (included in the plot for comparison). This means that the initial cracking mechanisms are not exclusively tensile cracking but shearing is already a part of the preliminary failure activity. It is also evident that there is a certain level of fluctuation between successive stages until final failure (stage 10 for beam #5 and stage 7 for beam #6), indicating that the failure mechanisms do not follow a smooth succession.

Fig. 9 shows the moving average of the RT for a sliding window of 200 successive hits for both representative beams, one of each beam type. The curve of the plain TRC hollow box (Beam #10) is contained mainly between 30-45 μs for most of the loading time and only at the end (corresponding to final stages 10 and 11) it reaches higher values as extensive pull-out activity is occurring. The curve of the hybrid beam (Beam #5) on the other hand shows stronger fluctuations. The RT values begin at 70 to 80 μs indicative for stronger shear from the start of loading and drops at 40 to 50 μs a few minutes later. After some fluctuations, at approximately 600 s it starts to exhibit an increasing trend reaching even 100 μs showing that at the final stage shearing mechanisms dominate.

Fig. 9. Rise time (RT) of two beams as moving average of recent 200 hits.
5. DIC results

In order to confirm the visual inspection of the broken specimens and to obtain an insight in the determining failure mechanisms, DIC observations are used to study the longitudinal strain field.

Fig. 10 represents these longitudinal strain fields just before (top) and just after (bottom) the maximum load of the hybrid beam, with a scale going from -0.35 % (purple) to 0.5 % (red). These strain fields indicate a strain increase in the central zone of the beam. This strain increase also results in sudden cracks in the concrete compression layer (localized green/yellow zones in the Fig. 10). As these cracks do not immediately grow through the complete concrete height and considering the continuous strain field between the concrete and the TRC box, there is still sufficient bond between the concrete compression layer and the box. Additionally there is no visual damage to the compressed concrete or TRC box, indicating that the only possible failure mode is the detachment of the CFRP strip at the bottom side. These observations confirm the conclusions drawn based on the AE measurements, where longer rise times and lower average frequencies are obtained, indicating a shear damage.

6. Conclusions

The use of AE enables to monitor the succession between fracture mechanisms. Specifically, for the hollow TRC boxes, the AE reveals that there is practically no change of fracture mechanism until the very end of the test when the material is close to ultimate failure. However, for the hybrid concrete-TRC beams strong fluctuations are noted while the average values of AE parameters correspond more to shear fracture characteristics. This is confirmed by the actual way that these beams failed (debonding between the CFRP strip and the TRC hollow box) as well as the surface observation of the DIC cameras (strain increase without visual damage at the TRC or concrete). This behaviour enables to assess in real time the behaviour and specifically the dominant fracture mode which is not easy with any other technique. From the AE activity recorded at low load stages, the longer signals emitted by the CFRP reinforced hybrid beams, show that the proportion between debonding and cracking events is different, being higher for the CFRP hybrid beams and lower for the plain hybrid beams.
References