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Fracture monitoring of lightweight composite-concrete beams

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ABSTRACT

Lightweight composite-concrete beams are advantageous in terms of installation, but their mechanical and fracture behaviour is not easy to predict due to their inherent heterogeneity. In the present study hybrid beams made of Textile Reinforced Cement (TRC) hollow boxes reinforced with a Carbon Fibre Reinforced Polymer (CFRP) strip and a concrete layer on top are subjected to bending. Their fracture behaviour is complicated as they can suffer from multiple failure mechanisms: matrix cracking, interface debonding or delamination. Herein, their mechanical performance is evaluated and monitored by Acoustic Emission (AE) and Digital Image Correlation (DIC). AE indices show that beams suffering from one single failure mechanism (cement cracking) exhibit nearly constant AE characteristics throughout loading. Beams additionally suffering from delamination exhibit longer AE waveforms of lower frequency compared to the pure matrix cracking. These tendencies are obvious from the initial part of the test, enabling predictions about the subsequent failure. More importantly and for the first time in related literature, the use of DIC enables to relate AE to the strain fields during loading, the final damage pattern and the ultimate failure mechanism.

1. 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 and strength of Fibre Reinforced Polymers (FRPs) [1,2]. However, these FRPs do not exhibit strong fire resistance, which is required in many building applications. A solution to this problem is offered by the low-cost Textile Reinforced Cements (TRCs) [3]. The Inorganic Phosphate Cement (IPC) [4], which can be combined with dense glass fibre textiles, results in a high performance TRC with a fibre volume fraction up to 25%. This material offers many advantages as it allows building with lightweight components, which exhibit an excellent behaviour under elevated temperatures. Therefore, this paper studies different hybrid geometries that are composed of a TRC box, possibly reinforced with a CFRP strip and/or completed with concrete on top. Due to the heterogeneity and complexity of the materials and the design, the mechanical and fracture properties of these hybrid beams are investigated by acoustic emission (AE) and digital image correlation (DIC) monitoring.

Apart from the mechanical results of the different types of beams, the main objective of this paper is to check if AE can follow the fracture process in composite construction elements. The failure mechanisms in a brittle cementitious composite like TRC include three main stages according to the ACK (Aveston, Cooper and Kelly) theory [5]. During the first stage both the cementitious matrix and the fibres contribute to the load bearing capacity, while damage is still negligible. The second stage occurs when cracks appear in the matrix until the matrix is fully cracked (matrix-cracking stage). Finally, in the third stage only the fibres are responsible for the load bearing capacity until the specimen fails due to fibre pull-out or debonding. On top of these mechanisms that concern the TRC, there can be debonding incidents between concrete and the TRC box as well as debonding of the CFRP strip from the hybrid beams. These additional mechanisms are triggered by shear forces and thus they are expected to lead to differences in the emitted AE waves when failure occurs compared to the cement cracking.

The first aim of this study is to check if AE parameter analysis can characterize effectively the failure behaviour of these innovative composite beams. In previous studies, AE was applied successfully to monitor damage in simple TRC coupons showing good sensitivity to the transition between the dominant failure mechanisms of matrix cracking on the one hand and delamination on the other hand [6]. The second aim is to go a step further and examine for the first time the correlation between the AE and

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the initial strain development before serious damage is inflicted in the structure. From the early stages of load application, stress and strain start to increase and can be captured by both DIC and AE. This AE activity is due to minor events and can help to predict the final failure behaviour since the simple load deflection curves cannot supply the detailed information on the transitions between failure mechanisms. This is a continuation of a research effort to build a methodology based on DIC and AE for monitoring the mechanical behaviour of lightweight hybrid composite elements for construction [7].

2. Acoustic emission background

Monitoring by AE sensors allows recording of all transient waves emitted by the damage propagation events [8]. On top of that, the different damage mechanisms (tension or shear) induce different crack tip motions, resulting in quite different AE characteristics. This enables passive monitoring and characterization of the dominant fracture mode [9,10]. 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, can be the most serious criterion in a health monitoring scheme [11]. Additional information about the failure mode can be supplied by analysis of AE waveform parameters. High frequency content of the waveforms are indicative for the tensile failure mechanism, while signals with long duration and Rise Time (RT) (see Fig. 1) indicate shearing as has been seen in composites, concrete and granite [12–15]. Another parameter that has been used in the aforementioned literature is the “RA value” which is the ratio of RT over the Amplitude which also offers strong fracture mode characterization power. Emphasis on the AE parameters is of particular importance in composite and complex materials as the fracture process is not straightforward to predict and the load-deflection curves are not enough to provide information on the mechanisms of fracture.

3. Experimental details

3.1. Geometry

Four hybrid designs are investigated in this paper. The first design (Fig. 2-a) is a TRC box composed of four glass fibre textile layers. The second design (Fig. 2-b) is similar but contains eight glass fibre textile layers. In the continuation of the text, both designs are referred to as the reference beams. The third design (Fig. 2-c) is a typical hybrid design with two CFRP strips (2.4 mm) inside the TRC box and 50 mm concrete on top of the 8-layers thick TRC box. The fourth design (Fig. 2-d) contains two CFRP strips (2.4 mm) outside the TRC box and 50 mm concrete on top of the 8-layers thick TRC box. The two latter types were designed to result in strong interlaminar shear stresses between the CFRP strip and the TRC box similarly to previous bending tests on the same geometry [7].

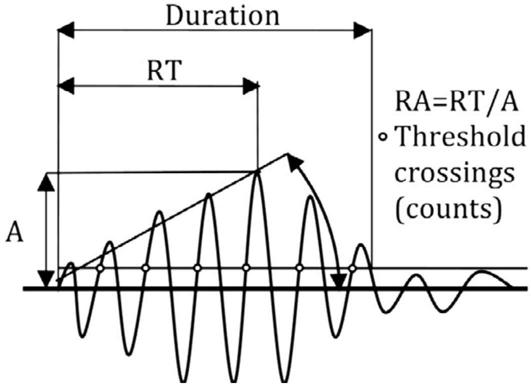

Fig. 1. Schematic representation of an AE waveform with some basic parameters. Average frequency AF is calculated by the number of counts over the duration.

3.2. Materials

The TRC hollow box is obtained by impregnating 2D random glass fibre textiles (300 g/m^2) with the IPC cementitious matrix. This results in an overall thickness of about 2.5 mm (in case of four layers; Fig. 2-a) or 5 mm (in case of eight layers; Fig. 2-b,c,d), a fibre volume fraction of about 20 % and an average tensile strength of 44 MPa.

To create the hybrid cross sections this TRC box is finished with a gravel layer (max. aggregate size of 4 mm) to enhance the connection between the box and the concrete compression layer. The concrete is mixed in the following mass proportions: 380 kg Portland cement CEM I 52.5 N; 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 39.7 MPa, measured on four prismatic specimens and afterwards converted into the standard cylindrical strength.

The CFRP strip is a commercially available strip [16], with a tensile strength higher than 2850 MPa and stiffness higher than 175 GPa (according to the supplier). Although CFRP strips provide a great enhancement in stiffness and strength, their weak point is the adhesive, which softens or even melts at elevated temperatures (e.g. in case of fire or direct sun radiation). In order to protect the CFRP from these direct external heating sources a reasonable choice is to bond the strip at the internal surface of the box (see Fig. 2-c) and not external, as commonly applied for strengthening existing structures with CFRP (see Fig. 2-d). However, in this design it is impossible to visually evaluate the damage phenomena related to this CFRP strip, leading to a more urgent need for acoustical NDT monitoring of this hybrid structure. In the framework of this study two beams of both of these choices (internal and external CFRP) are tested, resulting in very similar mechanical and acoustic behaviour. Along with the four plain TRC beams there are a total of eight beams reported in this paper.

3.3. AE monitoring

Two arrays of sensors were attached along the beams, one at the top and the other at the bottom (see Fig. 3). In the previous approach only one array was used on the concrete layer [7]. For the hybrid beams, the top array (sensors 1, 3, 5, 7) was attached at half-height of the concrete layer (top), while sensors 2, 4, 6 and 8 were attached at half-height of the TRC box (bottom). The boxes were only equipped with four sensors at half-height. The horizontal distance between successive sensors was 230 mm and the whole area covered 700 mm in the centre of the beam. Linear location was enabled for the two horizontal groups of sensors (one on concrete and one on TRC). Since the roughness of the materials (TRC and concrete) is not identical, this can induce differential coupling conditions to the two arrays of sensors (in the case of hybrid beams). For the purpose of consistency in this paper, it is deemed necessary to compare data taken from the sensors attached to the same material, which is the TRC box (bottom array of sensors in Fig. 3). The analysis below concerns all activity registered in “events”, meaning that they were received by multiple sensors within a limited window of time and their source was located within the gauge area.