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Flexural impact response of textile reinforced inorganic phosphate cement composites (TRC)

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HIGHLIGHTS

- Quantitative impact characterisation of textile reinforced cementitious laminates (TRC).
- Master curves, energy-time curves and energy profiles are obtained following the energy profiling method.
- Similar drop weight impact response to polymer matrix composites is verified.
- Effect of laminate thickness and impactor diameter is studied.

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ABSTRACT

This work presents the characterisation of the local low velocity impact behaviour of a high-performance fibre reinforced cementitious composite (HPFRCC) made of phosphate cement and different types of E-glass textile reinforcements. The so called "energy profiling method" that was used for quantitative characterisation is adopted from Liu et al. (2004) who introduced this methodology on polymer matrix composites (PMC). A series of plates reinforced with chopped strand E-glass fibre mats (fibre volume fraction of 24%) was impacted during drop weight tests, showing that this methodology is as well applicable to textile reinforced cementitious composites. Further, the effects of impactor size and plate thickness were investigated experimentally, and finally the obtained results were compared to literature data for polymer matrix composites.

1. Introduction

It is known from literature that laminated polymer matrix composite structures, eventually stiffened or in sandwich form, present superior specific energy absorption compared to their metallic counterparts. The different damage mechanisms such as delamination, fibre debonding, and fibre and matrix cracking, make them suitable candidates for high energy absorption applications such as protecting structures against low velocity impacts [1]. Besides the composite materials with polymer matrix (PMC), a new generation composites with a cementitious matrix has been developed during recent years, the so called High Performance Fibre Reinforced Cementitious Composites (HPFRCC). A definition for these cementitious composite materials was presented by Naaman and Reinhardt [2,3]. HPFRCC materials are characterised by their distinct tensile strain hardening behaviour which leads to an increased energy absorption capacity. Their characteristics can even be enhanced when making use of well-oriented and well-structured fibre textile reinforcement, as in textile reinforced cement or concrete (TRC) [4–7]. High tensile strength and post-cracking stiffness, as well as strict crack control, can be obtained with high volume fractions (even up to 20%) of different fibres (glass, carbon, aramid, ...) [8,9]. Some differences with polymer matrix composites can however be expected in the damage and failure mechanisms under impact loading: indeed, the cementitious matrix is stiffer but more brittle than most polymeric matrices, presenting a small failure strain in tension and shear; moreover, the bond strength between fibres and matrix is much lower. Several studies of TRC under dynamic tensile loading [10–12] or flexural impact loading [13–16] were published in recent years. They are however restricted to beam configurations, and the information on energy absorption capacity and damage mechanisms is limited.

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Low velocity impact behaviour is often assessed using drop weight impact tests. Even though a standard ASTM impact test, describing a single drop weight impact test and its configuration, is available for polymer matrix composites (PMC) [17], it does not allow the complete and objective characterisation of the impact behaviour of the composite plate material in relation with the occurring damage. In this paper, it is investigated whether a testing and analysis methodology, originally developed for PMC, can be applied to TRC composites in order to quantitatively and objectively characterise and compare their low velocity impact behaviour.

This methodology, called the energy profiling technique, was developed by Liu [18,19], and allows to link the quantitative results to the observed damage phenomena. A total of around 10–15 identical plate specimens of the composite material of interest are manufactured. Each specimen is tested in a drop weight impact test at a different impact energy level. The force and displacement histories are measured during the complete impact event, and are used for the interpretation of the results regarding the occurring damage phenomena. Essentially, the produced data are processed to obtain a "master curve" that contains all force-deflection curves of the tested plates, and a so called "energy profile" in which the absorbed energy for each test is compared to the impact energy as determined from the potential energy of the impactor before the test.

2. Experimental program

2.1. Test set-up

The used testing device is a drop weight tower which is schematically drawn in Fig. 2, and which was developed at the Department of Materials Science and Engineering at the University of Ghent [20]. The drop weight tower consists of an impactor, sliding along two guiding bars which are supported against a wall. The roller bearings are designed to minimize friction along the sidebars. The level of impact blow can be varied by changing the drop height of the impactor, with a maximum height of 3 m. It can be noticed that this changes simultaneously both the impact energy and the impact velocity. The end part of the impactor can be equipped with a hemispherical head with a diameter according to the user's needs. To enable the evaluation of the effect of the impactor head diameter, two hemispherical heads are used in this work. Their respective diameters are 50 mm and 70 mm. Results for a head diameter of 20 mm were reported elsewhere, and will be used as comparison [21]. The total mass of the impactor is around 7.9 kg. The square plate specimens are clamped along their four edges within a 250 mm by 250 mm square steel frame. Homogeneous clamping is obtained using 20 bolts equally divided over the four edges. The bolts are screwed with a torque key to assure an equal tightening at all positions.

As is shown in Fig. 1, the set-up is equipped with three sensors which are all placed on the impactor. The load sensor (blue), with a full range of +22,000/−2200 N, is positioned as close as possible to the head of the impactor in order to avoid interference of joints and bolted parts. The acceleration sensor (red), an accelerometer with a full scale of ±10,000 g, is placed on top of the impactor. The third sensor, which is indicated in green, is a magnetic displacement sensor. The data obtained from this sensor were however not sufficiently accurate to measure the deflections. These were obtained by double integration over time of the acceleration signal, the accuracy of which was verified by comparison with digital image correlation measurements on the impactor.

Furthermore, all drop weight tests are recorded with a high-speed camera which is placed in front of the impactor, providing a view on the plate during the impact event. The different damage mechanisms can be linked to the camera footage of the impact. The frame rate was limited to 4500 fps to ensure a maximum resolution of 1024 × 1024. The data measurements from the equipment on the impactor are synchronised with the data capturing of the camera. Triggering is performed based on a load threshold level of 200 N. The total time window for the measurements is set to 3 s (0.5 s before, and 2.5 s after the trigger point), which is sufficiently long to capture the impact event.

2.2. Test series – specimens

Four series of square plate specimens are manufactured by means of hand lay-up as described in [22]. A constant fibre volume fraction V_f of 24% was targeted. Their characteristics (average and standard deviation in parentheses) are given in Table 1.

CSM in the name stands for the used reinforcement: emulsion bonded glass fibre chopped strand mat type M705 manufactured by European Owens Corning Fiberglas, with nominal mat weight of 300 g/m^2. The numbers 20, 50 and 70 in the name stand for the impactor diameter ∅ in mm. Each laminate is build up with 8 layers of fibre mat, except series CSM-70-4, which contains only 4 layers. The range of drop heights h, and the corresponding maximum impact energy E_i are also given in Table 1 (more details are given in Tables 2–5).

3. Results and discussion

In the first part of this section, the damage phenomena and damage mechanisms during a low velocity impact event on IPC-TRC composite plates are studied using the energy profiling method proposed by Liu [18,19], supported by the high-speed camera images. Subsequently, the effect is investigated of changing test and specimen parameters on the impact characteristics. In the last part of this section, the obtained results for TRC are compared to results from literature obtained for PMC.

3.1. Damage characterisation

The data resulting from the impact tests are presented in Figs. 3–6 and Tables 2–5 in the next Section 3.2. In the present section, the general impact behaviour of IPC-TRC composite plates will be described, based on an excerpt of the data from series "CSM-20" (Fig. 3), which is represented in Fig. 2. The synchronisation of the camera footage (not represented here) with the test data is used to support the following observations:

- All force-deflection curves are quite similar in their ascending loading stage and descending unloading stage, except the rebounding stage (decreasing deflection in the unloading stage). As such, they form a mountain-shape master curve (see [21] for more details). The main damage in the plate occurs locally, even though the deflections of the plate can become relatively large;
- None of the force-deflection curves are returning to the origin after the impact, and are therefore not fully closed. This implies that for none of these impact events the energy absorption is fully elastic. Nevertheless, curves 1a and 1b of Fig. 2 (low impact energies) could be considered as closed curves, because of their pronounced rebounding section and the small contribution of the matrix damage. The absorbed energy for curves 1a and 1b remains less than half of the impact energy, and is resulting from local matrix indentation at the contact area and local debonding and slip between fibres and matrix. It is proposed to call this the indentation range;