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Energy dissipation capacity of fibre reinforced concrete under biaxial tension–compression load. Part II: Determination of the fracture process zone with the acoustic emission technique

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ABSTRACT

Part I of this paper showed that under biaxial tension–compression load the energy dissipation capacity of fibre reinforced concretes (FRC) is up to 30% lower than under uniaxial tension load. In this part, the extent of the fracture process zone (FPZ) was studied with the acoustic emission technique and the decrease of the energy dissipation will be explained.

It was found that plain concrete specimens have generally narrower/smaller FPZ compared to FRC specimens under both uniaxial tension and biaxial tension–compression load case. Under biaxial tension–compression load for both unreinforced and fibre reinforced specimens the FPZ tends to become slightly wider compared to the uniaxial tension load case. However with increasing biaxial compression stress ratios the specimens energy absorption capacity decreases. In case of biaxial load, the bond between the fibre and the matrix zone is affected by the lateral compression stresses, resulting in a smaller FPZ compared to the uniaxial load. This is believed to be the main reason for the lower dissipated energy.

1. Introduction

Pure tension, leading to opening Mode I fracture, is considered to be the most important and relevant loading condition in concretes, causing crack formations and damage directly influencing the durability of the entire structure. However, concrete structural elements, such as ground slabs or industrial floors, are rarely under pure uniaxial stress state, but prevailing under biaxial or multi-axial stress state conditions. The energy absorption capacity, crack resistance and damage propagation of the material under biaxial stress state usually differs significantly from that under uniaxial one and thus equal design approaches are not applicable. In order to develop safe and economic design of concrete structures it is important to know the fracture mechanical properties of the material under a range of different stress states as well as to their relation to the uniaxial values.

In fibre reinforced concrete (FRC) damage, micro- and macro-crack propagation is a rather complex process. As a result of the crack development in the fracture process zone (FPZ), micro cracks develop in the fibre–cement paste and aggregate–cement paste interfaces as well as in the cement paste itself. With a further increase of the load, macro cracks develop, which propagate through the concrete. Fibres in concrete mainly increase the resistance to crack propagation of the material due to the friction caused by the fibre pull-out mechanism or by fibre breakage. These mechanisms are present in both uniaxial tension- and biaxial tension–compression loading scenarios, however, as it was demonstrated in the accompanying Part I of this paper [1], the damage propagation and degree, and as a consequence the energy dissipation capacity of the material significantly changes. The energy dissipation capacity is significantly lower in the biaxial load case than in the uniaxial load case. So far, this phenomenon observed in FRC has not been explained.

The damage progression in FRC in uniaxial tension fracture tests has been comprehensively studied in papers collected in proceedings by Reinhardt and Naaman [2] and Gdoutos [3]. However, only a limited number of studies dealt with the damage and fracture energy of FRCs under biaxial loading conditions. In Elser [4], Tschegg et al. [5] and Tschegg [6,7] the fracture energy of different steel-, polymer- and glass-FRCs have been measured under uniaxial tension- and biaxial tension–compression load.

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Recently, increasing interest appeared in the investigation of the development and extent of the FPZ with the acoustic emission (AE) technique. Nomura et al. [8] and Weiler et al. [9] investigated the size of the FPZ of concrete and steel fibre concrete during the uniaxial three point bending test, whereas the group of Karihaloo conducted a comprehensive research work in investigation of the FPZ with the wedge splitting test (WST) [10–12]. However, all these studies investigated the development and extent of the FPZ under uniaxial tension load. To the knowledge of the authors the only results published so far dealing with the FPZ under biaxial tension–compression load are by Tschegg et al. [13] and Steller [14] of refractory materials and mass concretes of different aggregate sizes, respectively. As far as the authors are aware, no work has yet been published investigating the FPZ of FRCs under biaxial tension–compression load.

In the first part of this paper (Part I) it has been shown that under biaxial tension–compression load the energy dissipation capacity is up to 30% lower than under uniaxial load. In the second part of the paper, the size (width) of the FPZ will be comprehensively studied utilizing the AE technique. An explanation of the correlation between the shape of the FPZ and the decrease of the dissipated energy under biaxial load will be attempted and the possible corresponding governing mechanisms will be discussed.

2. Materials and specimens

Four different fibre types have been tested in concrete reinforced with straight and crimped synthetic macro fibres (FRC-S and FRC-E specimens) as well as with hooked-end and crimped steel fibres (FRC-D and FRC-T specimens). The mean compressive cube strength of plain concrete was 48.3 N/mm^2 and the dosage of fibres in the matrix was 0.5% and 0.4% by volume for synthetic macro and steel fibres respectively.

The test specimens were cubes with the dimensions $150 \times 150 \times 120\ mm^3$. For each different concrete mixture, 6 identical specimens were tested. The detailed concrete mix design, fibre properties and specimen setup are summarized in the accompanying paper (Part I of this paper).

3. Determination of the fracture process zone with the acoustic emission technique

The fracture energy of the specimens was determined using the Wedge Splitting Test (WST) according to Tschegg [15,16] (see also Part I of this paper). During the WST, the development of the FPZ was tracked and recorded by employing the AE technique. On each lateral side of the specimens two sensors (1, 2 and 3, 4) were fixed (Fig. 1). All four sensors formed one vertical plane that was perpendicular to the fracture plane.

The AE technique enables the determination and tracking of the damage within the specimens during entire load application. It is based on the principle that if the limit of elasticity in the region of the notch tip is exceeded, micro cracks will develop and damage will occur. The stored elastic energy is then released in a sudden manner generating sound waves. The sound waves are detected by four sensors of the AE device, which are attached to the specimen. They are then converted into electrical signals and transmitted to the recording device. Due to the difference in transition times to the sensors, the origin of the event and the degree of damage can be determined. A software calculates the location of the event (x and y coordinates) within the specimen and the amplitudes of the sound events. When the amplitude of the sound wave exceeds a defined threshold, an event (or damage) is recorded and represented with a dot in the cross section. Additionally, the chronology of sound events within the load-crack mouth opening displacement (CMOD) curve can be displayed. It enables the comparison of the frequency of occurrence of micro-cracks at a particular CMOD. The accuracy of the AE technique is around ±5 mm, some events could also occur within the specimen's notch. As a consequence of the combined compression and tension load, events also occur in remote parts of the specimens. These events would not occur under pure compression load or would occur later at higher compression load ratios.

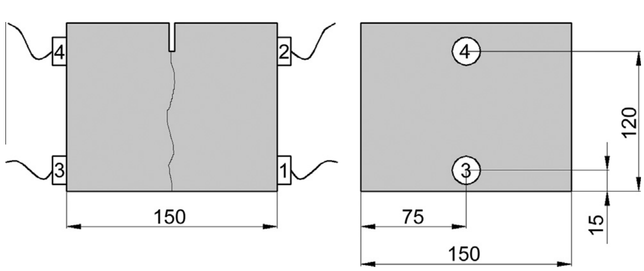

Fig. 1. Arrangement of the sensors (1–4) on the wedge splitting specimens during the acoustic emission measurement.

4. Results and discussion

4.1. Extent of the fracture process zone

In case of biaxial tension–compression load, prior to the application of the tensile load, the specimens are subjected to compression stresses (σ_1) equal to different ratios of the concrete's compressive strength (f_c). The following normalized compression stress ratios were applied: $\sigma_1/f_c = 10\%$, 20%, 35% and 50%. As a result of this pre-applied compression stress, a certain level of damage already exists within the concrete matrix. With an increase of the applied compression stress ratio, the volume affected by the damage increases as well.

When this pre-damaged section of the FRC is subjected to tension, further AE events occur indicating further damage. Fig. 2 shows the location of all events within the specimens at the end of the test under uniaxial load ($\sigma_1/f_c = 0\%$) and under biaxial tension–compression load of $\sigma_1/f_c = 50\%$. In all figures the pre-damage, caused by the compression load being applied, is excluded.

The width/size of the FPZ is denoted with an ellipse and is determined as follows: For each particular specimen within one series, the mean value of the horizontal distance of all events from a certain reference point (edge or middle line of the specimen) together with the standard deviation was determined. The standard deviation actually represents the width or size of the FPZ. A low standard deviation indicates a narrow/small FPZ, whereas a high standard deviation results in wide/large FPZ. The mean value of all 6 standard deviations within one test series represents the width/size of the FPZ of the particular test series. The absolute width/size of the FPZ for all specimens under uniaxial and different biaxial tension–compression loads is shown in Fig. 3a. The normalized width of the FPZ (Fig. 3b) is calculated as the ratio of the size of the FPZ under biaxial load to the uniaxial value. In both figures best fit linear trend lines are inserted through the mean values.

Generally, plain concrete specimens have a narrower/smaller FPZ compared to all other FRC specimens under both uniaxial and biaxial load cases (Fig. 3a). The longer the fibre the larger the FPZ is becoming, which is even more pronounced when the fibre anchorage system is at the end of the fibre (hooked-end). The difference seems to be more distinctive in the case of uniaxial load than in case of the biaxial tension–compression load. Plain concrete is a highly brittle material and if loaded, the damage within