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Energy dissipation capacity of fibre reinforced concrete under biaxial tension–compression load. Part I: Test equipment and work of fracture

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ABSTRACT

The objective of this research was to analyse the differences in the dissipated energy under uniaxial tension and biaxial tension–compression load of fibre reinforced concretes using the Wedge Splitting Test. Under biaxial load the specimens were subjected to compressive stress ratios from 10% to 50% of the concrete compressive strength perpendicular to the direction of the tensile load.

Under biaxial tension–compression load the energy dissipation capacity of the specimens decreases compared to the uniaxial tension load case on average 20–30%. It is believed that the decrease is a result of the damage mechanism of the concrete matrix and deterioration of the fibre–matrix and/or aggregate–cement paste interfaces in case the section is additionally loaded with compression stresses. This indicates that dimensioning of concrete elements under biaxial stress states using material parameters obtained from tests conducted on specimens under uniaxial tensile load is unsafe and could potentially lead to a non-conservative design.

In the second part of this paper the extent of the fracture process zone under uniaxial tension and biaxial tension–compression load will be examined with the Acoustic Emission technique and the reasons for decrease of the energy dissipation capacity under biaxial load will be further discussed.

1. Introduction

Concrete structural elements have extremely high compressive strength and relatively low tensile strength capacity. Concrete tensile cracks appear already under a tensile load of 1/10 of the concrete's compressive strength. Pure tension leads to opening Mode I fracture and is considered the most important one for concrete, causing crack formations and damage directly influencing the durability of the entire structure.

However, only a limited number of concrete structural elements are loaded under pure uniaxial tension. The majority of structures, such as columns, slabs, shells, and thin-walled constructions are biaxially- or multiaxially loaded. One of the most frequently occurring stress states is biaxial tension–compression, where compression acts in one direction and tension in the direction perpendicular to it. This stress state also initiates Mode I fracture. In order to provide a safe and economic design of concrete structural elements, it is inevitable to have experimental information about the mechanical and fracture mechanical properties of the material under various stress states occurring in the structure's service life. Exactly this is the objective of this research; to experimentally investigate the fracture mechanical properties of concrete and different fibre reinforced concretes (FRC) under one of the most frequently occurring stress states: biaxial tension–compression load.

So far very limited research has been published about fracture mechanical characterization of concrete under different types of biaxial loading conditions. Some research has been conducted on un-notched specimens loaded under biaxial compression load [1–4]. Zi et al. tested the strength of different concretes under biaxial tension [5,6]. Weenheijm et al. [7] investigated the fracture behaviour of concrete on notched specimens with the "Split-Hopkinson-bar" technique under compression and tension. The "rate-effect" as well as the pre- and post-peak part of the load–displacement curves have been determined and the specific fracture energy has been measured. Interesting results were reported by Meier [8] who investigated the tensile strength and the resulting failure curves of concrete and FRC under biaxial tension–compression load and obtained their fracture mechanical

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properties. Tschegg et al. [9] and Elser [10] investigated fracture mechanical properties of different concretes and cement bonded materials under biaxial tensile–compression load and found out that the notch tensile strength and the fracture energy decreases with the application of an additional compression load perpendicular to the acting tensile load. Subsequently, Elser et al. [11] and Tschegg [12] investigated different steel and polypropylene fibre reinforced concretes, where a similar decrease of the fracture energy has been observed.

In this work the dissipated energy in terms of work of fracture of plain concrete and different steel and synthetic FRCs under uniaxial tension load and under biaxial tension–compression load have been studied. Under biaxial load five different compressive stress ratios of 10%, 20%, 35% and 50% of the concrete compressive strength has been applied. From the load–displacement diagrams, the notch tensile strength and the work of fracture is being determined. The differences in the value of the notch tensile strength and the dissipated energy under uniaxial- and biaxial load will be discussed in detail. Additionally, the trend of the notch tensile strength and the dissipated energy with increasing compressive stress ratio will be comprehensively analysed.

2. Materials

2.1. Matrix design

The aggregate used for the concrete matrix was gravel lime stone with maximum sizes of 4 mm and 16 mm for fine and coarse aggregate respectively. Cement CEM II/42.5N was used and the water/cement ratio was 0.64. The concrete mixture has a density of 2483 kg/m^3 and mean compressive cube strength of 48.3 N/mm^2 at the age of 28 days. The mix design is given in Table 1.

Four different types of fibres have been used as reinforcement (Fig. 1): straight and deformed synthetic macro fibres (type S and E) as well as steel fibres with hooked-end and deformed fibres (type D and T). The synthetic macro fibres of type S were very soft and deformable while the E fibres were rather stiff. The properties of the fibres are summarised in Table 2. The dosage of fibres in the concrete matrix was 4.5 kg/m^3 for synthetic macro fibres and 30 kg/m^3 for steel fibres. This resulted in a 0.5% and 0.4% of fibre content by volume respectively. The mix design of the composite and the mean values of the density and compressive strength are summarized in Table 3.

2.2. Specimens

The specimens for fracture mechanical tests have the dimensions of 150 × 150 × 120 mm^3 with a 20 mm long and 4 mm wide starter notch cut at the top (Fig. 2). For uniaxial tests the specimens require a rectangular groove on the upper side for the installation of the load transmission pieces. This has been achieved by gluing two stone pieces on the top face (Fig. 2a). Specimens for biaxial test (Fig. 2b) do not need the groove since the setup of the test equipment is such that the compression plates already form the rectangular groove needed. The concrete cube moulds used for specimens have been always filled from the top. The compaction of the specimens was achieved by placing the specimens onto a vibration table. After compaction, the top surface was finished using a trowel. After one day the specimens were demoulded and stored for 28 days in a water bath at 20 °C. For each different concrete mixture a series of 6 identical specimens were tested.

Table 1
Concrete matrix mix design.

Component	Quantity (kg/m^3)
Sand 0/4 mm	1200
Coarse aggregate 4/8 mm	260
Coarse aggregate 8/16 mm	540
Cement	265
Fly ash	40
Super plasticizer	1.5
Water	170

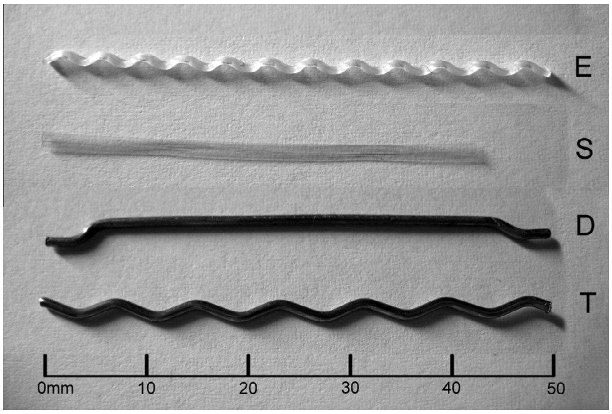

Fig. 1. Geometry of the fibres: *E* – deformed synthetic fibres, *S* – straight synthetic fibres, *D* – hooked-end steel fibres and *T* – deformed steel fibres.

3. Experimental procedures

3.1. Uniaxial and biaxial Wedge Splitting Test

The uniaxial and biaxial Wedge Splitting Test (WST) method developed and patented by Tschegg [13–15] has already been extensively described in the literature [10–12], thus in this work only a short description will be given. Fig. 3 shows the WST method for uniaxial tensile load for a cubic specimen in a simplified form. The specimen is positioned on a narrow linear support and the two load transmission pieces and a slender wedge are inserted in the groove. The load, F_M, produced by the testing machine is transferred by the load transmission pieces from the wedge into the specimen, which leads to the splitting of the specimen. The friction between the wedge and load transmission pieces (equipped with ball bearings) is negligibly small (<1%) [14]. The vertical force, F_M, of the testing machine is converted to a large horizontal force, F_H, and into small vertical force, F_V that does not disturb the propagation of the crack [14]. The splitting force F_H breaks the specimen in mode I.

Under biaxial loading (Fig. 4) the cubic specimens are first subjected to compression stresses (σ_1 on Fig. 2b), provided by hydraulic cylinders and then additionally to tensile stresses (σ_2) produced by the wedge. In such a way a Mode I crack is produced, which propagates in a stable manner through the specimen. The two loading frames with the hydraulic cylinders are mounted on the specimen and the support for the two gauges (for measuring of the horizontal displacement) is fixed in the line of action of the horizontal forces applied by the wedge. The horizontal displacement, the crack mouth opening displacement (CMOD), is determined at the height of the load application line on both sides by linear variable differential transformers (LVDT). The LVDTs are installed on a metal frame. The two transducers enable an averaging of the horizontal displacements and on the other hand serve as crack path detectors. In case the crack deviates from the vertical path and runs diagonally to the starter notch, the test result are disregarded. The two tightening frames and other parts of the WST equipment, which result in a biaxial load, are only fixed on