Cement & Concrete Composites 34 (2012) 166–171

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Tensile and bending behaviour of a strain hardening cement-based composite: Experimental and numerical analysis

Jean-Louis Tailhan, Pierre Rossi *, Claude Boulay

Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR, previously L.C.P.C.), Université Paris-Est, France

ARTICLE INFO

Article history:
Received 9 December 2010
Received in revised form 11 October 2011
Accepted 15 October 2011
Available online 20 October 2011

Keywords:
Ultra-high performances cement-based composite
Bending behaviour
Uniaxial tensile behaviour
Numerical modelling
Inverse analysis

ABSTRACT

IFSTTAR has developed a Multi-Scale Cement Based Composite (MSCC). This composite material is strain hardening in tension and exhibits ultra-high strengths as well in both compression and tension. The main research objectives for the present paper are the determination of the strain hardening properties of the material: using a newly developed tensile test in conjunction with a finite-element-based inverse analysis, the input parameters of an (adapted) numerical model can be identified. Therefore, numerical simulations can be performed to describe the bending behaviour of a thin slab having a thickness representative of the corresponding industrial application.

The main conclusions of this study are:

- The studied material clearly exhibits strain hardening in tension with a uniaxial tensile strength of about 20 MPa and a modulus of rupture of about 50 MPa.
- Elasto-plastic behaviour with strain hardening is a relevant mechanical model (for the studied material) for designing (by the finite element method) structural elements behaving principally in bending.

1. Introduction

Based on the "multi-scale fibre reinforcement" concept proposed by Rossi et al. [1], a Multi-Scale Cement Based Composite (MSCC) has been developed and patented [2–8]. This cement based composite is obtained by incorporating a high percentage of steel fibres in an ultra-high performance matrix (with a compressive strength of more than 250 MPa). This fibre reinforcement is composed of three different geometries (different lengths and diameters) of fibres, each one playing a particular role in relation with the matrix cracking process at a corresponding scale. By this way, a real strain hardening material is expected. The steel fibre reinforcement of this MSCC (the total volume percentage being equal to 11% by volume of concrete) can be summarised as follows:

- *First dimension:* steel wool with a fibre length less than 2 mm (between 1% and 3%).
- *Second dimension:* straight drawn fibre 5 mm long and 0.15 mm in diameter (between 4% and 6%).
- *Third dimension:* straight drawn fibre 20 mm long and 0.25 mm in diameter (between 1% and 3%).

Further details regarding the material composition and its processing are reported elsewhere [2–8].

Taking into account the *cost/performance* ratio for this kind of material, it is necessary to optimise its industrial use. In 2-D thin structures (e.g. plates, thin slabs or shells) when they are principally subjected to bending or to point loads, the material is essentially in a local tensile state of stress. As a consequence, to design a plate (or a thin slab) with a finite element model, it is important to know, and then to determine, the tensile behaviour of the material.

The principal objective of this study is to demonstrate that a mechanical model taking into account "classical" elasto-plastic behaviour with strain hardening is pertinent to design structures made with the studied material. To achieve this objective, the following steps are chosen:

- First, a uniaxial tensile test is developed and performed to verify that the studied material is really a strain hardening one. This type of test is not easy to perform correctly on this kind of material (as discussed in Chapter 2).

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* Corresponding author. Address: LCPC-58, Boulevard Lefebvre – 75732 Paris Cedex 15, France. Tel.: +33 1 40 43 52 95; fax: +33 1 40 43 54 93.

E-mail address: pierre.rossi@lcpc.fr (P. Rossi).

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doi:10.1016/j.cemconcomp.2011.10.005

- Secondly, bending tests are performed on specimens representative of industrial structural elements considered as pertinent applications with the studied material.
- Third, a finite element model is used to simulate the experimental bending tests. The values of the model parameters are determined by a semi-inverse analysis.
- Lastly, possible scale effect problems related to the values of the model parameters are analysed.

During this study, only the pre-peak behaviour is considered for both experimental and modelling aspects (in both bending and uniaxial tension). This means that the material softening behaviour is not considered and analysed in this work. The reason is that only the strain hardening behaviour of the material is retained to design structures made of the studied material. This design strategy seems to be suitable when 2-D thin structures are considered.

2. Uniaxial tensile test development

It is interesting to note that some researchers have worked on the development of uniaxial tensile tests adapted to study ultra-high performance cement-based composites [9,10]. In the present study, the objective of this tensile test is to determine the uniaxial tensile behaviour of the studied MSCC when it is used in a thin slab element (or plate). So, the fibre distribution must be representative of the one which exists within a thin slab or a plate, i.e. it must be orthotropic. Therefore, it has been decided that the width of the specimen, in the uniform tensile zone, has to be at least four times larger than the length of the largest fibre: a length of 10 cm seems relevant.

Other criteria also intervened in the definition of the specimen geometry:

- Strain and stress fields in the specimen zone where strain measurements are carried out should be as uniform as possible, and over a sufficient length with respect to the length of the largest fibre: a measurement base of 20 cm is therefore selected.
- Specimen must not crack in the zone located close to the interface between the specimen and the test/machine grip. In this zone, the strain and the stress fields are not uniform.
- Previous studies [9] on cement composites, with a matrix similar to that of the studied material, indicated that this matrix starts to crack for a tensile stress of about 8 MPa. In comparison with these previous studies, the uniaxial tensile strength of the studied MSCC can reach 25 MPa, i.e. approximately three times the tensile strength of its matrix.

According to the criteria and above remarks, the specimen dimensions have to respect the following conditions: 5 cm thickness, 10 cm width, and 20 cm length, in the zone where strain and stress fields must be as uniform as possible. Moreover, the specimen must have a 30 cm width at the interface level with the press (so that stress is approximately three times lower than that of the zone where strain measurements are carried out).

Taking the works of Do [11] and Behloul [12,13] as a starting point, a dog bone specimen with 75 cm of overall length is retained at this step of the study. The specimen, glued to the press by using an adaptation block (made of aluminium), has its geometry (and dimensions) optimised by numerical simulations using the CESAR-LCPC finite element code. This optimisation aims to:

- generate uniform tensile stress in the central part of the dog bone specimen;
- generate much lower tensile stresses (compared to the central part of the specimen) at the *specimen/press* interfaces.

Taking into account the specimen shape and in the aim to avoid tensile stress appearance as consequence of material restrained shrinkage during its stay in mould after casting, particular cares, following those mentioned by Behloul [13], are taken. The moulds are manufactured to be able to run nine specimens in three batches. Specimen and mould geometries are given in Fig. 1. Specimens are cast flat and are vibrated during casting on a mobile plate. All specimens have undergone a heat treatment (in a drying oven at 90 °C for 4 days, 48 h after their removal from mould).

After this cure, the upper and lower faces of each specimen are ground with a surface grinder machine. Twenty minutes before the tests, the specimens are glued, with a methyl methacrylate resin, between two platens, made of aluminium alloy, rigidly fixed on the cross-heads of the testing machine.

To ensure that no crack appears in glued interfaces during the test, it has been decided to add complementary supports placed on specimen concave parts. These supports are connected to the specimen and to the aluminium platens via four 20 mm diameter prestressed rods (Fig. 2). In order to design them, finite element calculations, still using the CESAR-LCPC code, were performed taking into account all experimental set-ups (that means with the prestressing of the interface zone between the specimen and the machine). The calculations showed that tensile stresses at *specimen/press* interfaces reached 8.5 MPa when it reached 27 MPa in specimen central part (where the stress distribution was found to be homogeneous).

Four specimens are tested following the experimental set-up described above. A jack displacement rate of 0.1 mm/min is imposed.

3. Bending tests

In this study, prefabricated thin slab element (or plate) is considered as a structural application of the MSCC. Mechanical tests are thus carried out on specimens representative of these types of structural elements. In order to optimise specimens dimensions with respect to scale effects and to preferential orientation of fibres, it is selected to retain the following dimensions for the specimens: 600 mm length, 200 mm width and 40 mm thickness.

The specimens are cast flat and vibrated during casting on a mobile plate. *Specimen width/largest fibre length* ratio (200/25) and specimen casting procedure allow an orthotropic orientation of fibres representative of a real slab element. A four point bending test

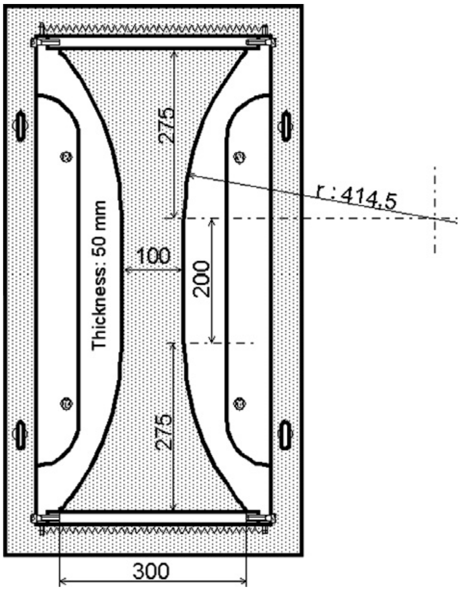

Fig. 1. Specimen mould and geometry related to the tensile test.