Cement and Concrete Composites 67 (2016) 1–11

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

Predicting the flexural response of steel fibre reinforced concrete prisms using a sectional model

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ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form
1 November 2015
Accepted 26 December 2015
Available online 30 December 2015

Keywords:
Steel fibre
Concrete
Material characterisation
Inverse analysis
Sectional analysis
Bending
Uniaxial tension

ABSTRACT

The material characterisation of steel fibre reinforced concrete (SFRC) continues to be an ongoing topic of debate in the scientific community. When designing a structural element made of SFRC, its defining characteristic is its post-cracking residual tensile strength. Theoretically, a uniaxial tension test is the ideal test in gathering these parameters; however these tests are expensive in time and testing. Consequently, much effort has been placed on inferring the post-cracking properties of SFRC from simpler tests, such as a notched prism in bending. In this paper, the sectional analysis procedure of Zhang and Stang (1998) is adapted with the inclusion of the variable engagement model to describe SFRC in tension. The model is shown to accurately capture the load–deformation characteristics of the tested specimens and allows for the explicit identification of the components resisting load.

1. Introduction

The adoption of fibres in concrete can no longer be considered as new or novel; fibres have been used to reinforce brittle materials, such as straw in mud for masonry construction dating back to the Babylonian and Egyptian eras. From a modern perspective, research in steel fibre reinforced concrete (SFRC) has a history of approximately 50 years with seminal research conducted in the early 1960s by Refs. [1,2] on closely spaced and randomly orientated wire reinforcement forming the basis of the fibre reinforced concrete we know today. While the latest fibres commercially available in the marketplace, and their technological development, bear little resemblance to those used by Romualdi et al. or indeed the Babylonians and Egyptians, the concept of using fibres to bridge and resist the propagation of micro and macro cracks that occur in a weak cementitious matrix due to various states of tensile stress and strain remains unchanged [3].

The introduction of fibres into concrete was originally intended to enhance the tensile strength of the concrete matrix, by delaying the widening of micro-cracks but without consideration for material toughness [4]. With increased interest of the material, through research in the 1970s, particularly by Refs. [5–9], it became evident that the addition of fibres significantly increased the toughness or post-cracking energy absorption characteristics of the otherwise brittle concrete, without significantly affecting the cracking strength of the matrix.

The most important property when considering the design of a structural element manufactured with SFRC is its post-cracking, or residual tensile strength. Once the concrete matrix has cracked (at a stress equivalent to f_{ct}), the fibres transmit stress across the crack and, in the process, provide some resistance to the widening of the crack. As the crack widens, provided that the tensile strength of the fibres is not exceeded, the fibres will gradually pull out of the matrix. Thus, unlike plain concrete, an appropriately reinforced SFRC specimen will not completely fail after crack initiation but some residual strength after cracking will be available. The resultant of this is the increase of the work of fracture and this is referred to as toughness or fracture energy. Quantified, fracture energy is represented as the area underneath the σ-w curve (see Fig. 1).

Of interest to researchers and practitioners, alike, is the determination of the complete σ-w curve (similar to that presented in Fig. 1) for SFRC. However, in order to obtain this curve, appropriate test methods are required. Some researchers believe that the

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http://dx.doi.org/10.1016/j.cemconcomp.2015.12.007
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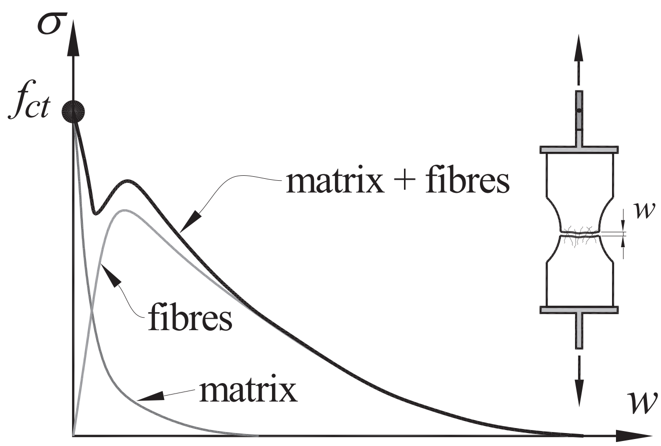

Fig. 1. Stress versus Crack Opening Displacement (COD), w for SFRC.

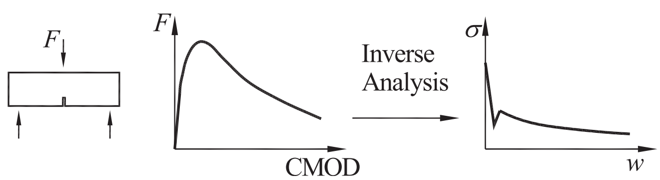

Fig. 2. Indirect approach to determine the tensile properties of SFRC.

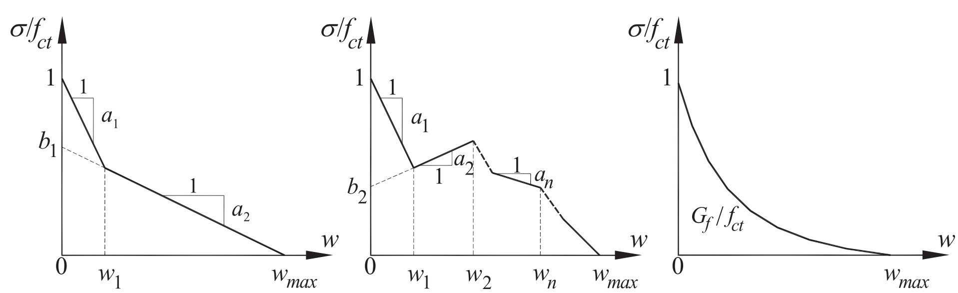

Fig. 3. Different σ-w relationships used in inverse analysis.

determination of the σ-w relationship is an intricate problem [10]. In the case of brittle and quasi-brittle materials, such as plain concrete, the direct tensile strength is often estimated using an indirect method such as by the modulus of rupture or split-cylinder test. However, where a greater degree of ductility exists in the σ-w softening curve, such as in the case of SFRC, the use of such indirect testing measures to determine the tensile strength, and shape of the post-cracking softening curve, of the material can be problematic.

In principle, a direct uniaxial tension test is the ideal test that should be used in gathering the softening, or residual, parameters of SFRC experimentally [11–20]. The manufacture and testing of uniaxial tension test specimens, however, is considered to be costly in time and requires specialised equipment unavailable in most laboratories [20–22].

As an alternative to direct tension testing, indirect methods have been proposed by many researchers. In these tests, a single crack is made to run in a notched, or un-notched, prismatic specimen (in three- or four-point bending) while measuring load and displacement. From these results a softening curve is then inferred by means of an inverse analysis [10,16,23–28]. In this paper, the sectional analysis procedure set out in Ref. [24] is adapted with the inclusion of the variable engagement model (VEM) of Voo and Foster [29–31] to describe the SFRC in tension.

2. Inverse analysis

Indirect methods have been proposed over the last two decades as an alternative to conducting uniaxial tensile testing to obtain the σ-w relationship of SFRC from prism bending tests (Fig. 2). One such method is the inverse analysis procedure and this approach has been investigated by a number of researchers [10,14,23–28].

Generally, the first step of an inverse analysis procedure is to assume the shape of the softening curve. As the shape of the σ-w curve can be complex, it may be necessary to simplify the relationship to linear (rigid or descending), multi-linear or exponential

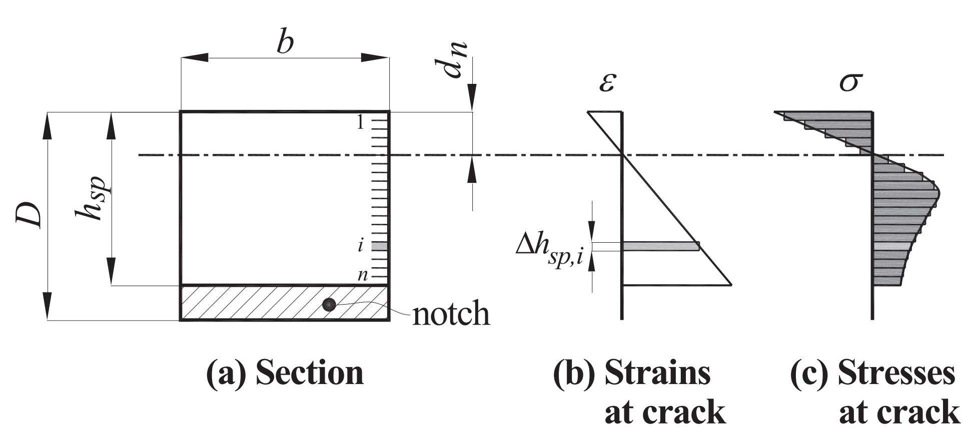

Fig. 4. *fib* MC 2010 inverse analysis (Fig. 5. 6-4 *fib* MC 2010).