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Tension stiffening in textile-reinforced concrete under high speed tensile loads

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ABSTRACT

Damage mechanism in glass textile-reinforced concrete (TRC) with and without the addition of Alkali resistant short glass fibers under high speed tensile loading was investigated. The high strain rates ranging from 25 to 100 s^{-1} were achieved using a high speed servo-hydraulic testing machine. Image analysis by means of digital image correlation (DIC) method was used to obtain the evolution of crack width which was subsequently correlated with stress response. The non-uniform strain distribution was characterized as three distinct response zones of localization, shear lag, and uniform strain and quantitatively measured in each zone. Mechanism corresponding to the basic aspects of tension stiffening modeling were identified by computing the average stress in the matrix phase between two cracks. The width of crack localization zone as well as crack spacing were also obtained using DIC as indications of bonding properties. A finite difference method simulating tension stiffening behavior was employed to predict crack spacing and stress–strain responses of TRC systems. Improvements in bond properties and mitigation of cracking with the addition of short fibers were verified using multiple methods.

1. Introduction

The use of textiles as reinforcement in cement based systems greatly enhances the strength, strain capacity, and work-to-fracture of the composite by means of multiple cracking mechanism and leads to strain hardening behavior. The outstanding mechanical performance can be utilized for load bearing structural members, structural panels, impact and blast resistance, repair and retrofit applications [1,2]. The mechanical response and distributed damage zones have been studied under both static and dynamic loads using conventional technique [3,4]. Fig. 1 illustrates the schematic tensile stress–strain behavior of TRC represented by initiation of cracking that leads to multiple cracking mechanism. Four distinct stages of the stress–strain curve are identified. Stage 1 corresponds to the linear-elastic range where both matrix and the fiber behave linearly and the rule of mixtures is applicable. The linear elastic stage is terminated by the initiation of first crack at point A, when the matrix cracking strength $\sigma_{m,cr}$, which is generally referred to as the bend over point (BOP) is reached. Stage 2 represents the stage between the initiation of the first crack and its propagation across the width of the sample which may cover a sufficiently notable stress range for large fiber contents. Experimental observations on more than 100 data sets have indicated that there is a range of stress from BOP^{-} to BOP^{+} that characterizes this stage [5]. For brevity this range is shown to correspond to a single stress level (horizontal line). The stiffness gradually degrades in stage 3 due to the formation of distributed cracks at regular intervals. The load carrying capacity of uncracked matrix segments does not vanish, as referred to tension stiffening. After the completion of cracking phase and initiation of debonding, progressive damage takes place in Stage 4 by means of crack widening due to fiber pull out and fracture.

When the tension tests are conducted at high speed, a high sampling rate in the range of 10–1000 kHz [6] is required to acquire sufficient data points within a few milliseconds. Additionally, slipping in the grips and the inertial effect of mass of grips and transducers to the samples during dynamic testing may affect the test results and limit experimental accuracy. Therefore the strain measured at an isolated spot or within a gauge length by conventional devices such as LVDT, extensometer and strain gage is

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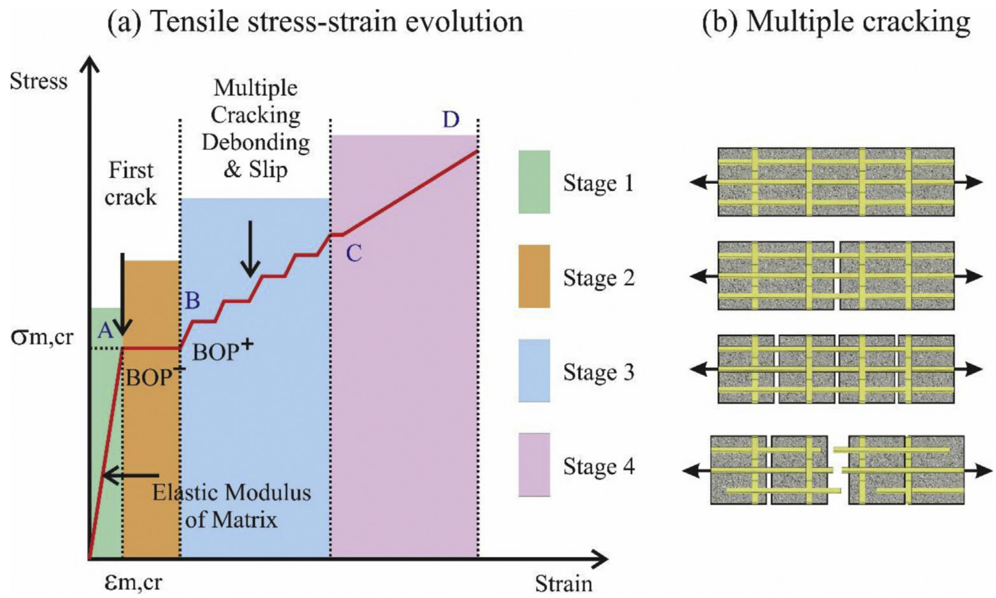

Fig. 1. Schematic presentation of the tensile behavior of TRC including (a) tensile stress–strain evolution, (b) multiple cracking mechanism.

insufficient to study the inhomogeneous results. Digital Image Correlation (DIC), is a non-contacting optical full field deformation measurement approach that can better address the complex behavior of this class of materials. DIC technique was developed by Sutton et al. [7] and Bruck et al. [8] and has been widely applied for composites, and reinforced concrete sections [9–11] while its application in cement-based composites tested under dynamic loads is limited [4,12,13].

Full field displacement measurements can be used for numerical analysis of strain softening and parameters of localization by extensions of smeared crack continuum models [14,15] or discrete crack models that are based on non-linear fracture mechanics [16–18]. The size of the localization zone is an important interaction parameter between the fiber effect, stiffness of the cracked region, and fiber debonding due to crack opening. Size of the localization zone is also significant from modeling point of view as it prevents snap-back phenomenon and numerical instability when the energy dissipation is localized in a small representative volume element [19,20]. Crack spacing parameters affect tension stiffening and localization length and according to Bažant and others, relate the volumetric energy dissipation per unit volume to that per unit cracked surface, and in doing so affect the mesh dependency of numerical models with distributed damage [21,22]. The stress-crack width (σ-ω) constitutive law has been widely used as an input parameter in the design of fiber reinforced concrete (FRC) [23,24]. The present experimental approach measures the crack width, spacing, and length of localization in a hybrid reinforced TRC tensile specimen using the DIC technique.

Barhum et al. [25,26] studied the influence of short fibers on the mechanical properties of TRC under static tensile loads and observed macro and micro-cracks. The bridging of micro-cracks by well distributed short fibers inhibits crack growth, promotes additional cracking, and subsequently their coalescence into formation of macro-cracks. As a result of microcrack formation and homogenization in matrix, a higher level of stress at BOP is carried, but the improvement in tensile stress diminish with the strain and only a moderate increase in ultimate tensile strength was observed. Silva et al. [3] studied this behavior under high strain rates and found a slight reduction in the energy absorbed with the addition of 0.5% of short glass fibers. The mechanisms leading to this reduction are still unclear and may be attributed to the compaction and porosity of the final product.

In the present work on tension stiffening, plain mortar and TRC samples with and without short Alkali resistant glass fibers (ARG) are tested under high speed tensile loading condition at three different strain rates: 25 s^{-1}, 50 s^{-1} and 100 s^{-1}. DIC was used to investigate the distributed cracking and damage as well as the full field distribution of tensile strain. Moreover, a finite difference model developed based on the tension stiffening behavior was used to simulate the experimental results. The assumption and mechanisms employed in the model were verified by DIC observation.

2. Experimental program

2.1. Materials and processing

A finely grained matrix was used in making the mortar and TRC samples with the mix design summarized in Table 1. The average slump flow value measured with a small cone (bottom diameter 100 mm, top diameter 60 mm, height 70 mm) was 200 mm. Polymer-coated biaxial fabric made of AR-glass was used in 3 layers as reinforcement. The degree of reinforcement was calculated for one layer of fabric in volume as 66.33 mm^2/m in both longitudinal and transverse directions. The fineness and the mean spacing of the weft and warp threads were 2*640 tex and 7.2 mm, respectively. Dispersed ARG with an average diameter of 14 μm and length of 6 mm were used in a total volume fraction of 0.5%. The ARG has a density of 2.68 g/cm^3, tensile strength of 1700 MPa and Young's

Table 1
Matrix composition (kg/m^3).

Water-to-binder ratio	0.37
CEM III B 32.5 NW-HS-NA	632
Fly ash	265
Micro silica suspension[a]	101
Fine sand 0/1	947
Water	234
Superplasticizer	11

[a] Solid:water = 50:50.