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Correlation of constitutive response of hybrid textile reinforced concrete from tensile and flexural tests

Barzin Mobasher [a,*], Vikram Dey [a], Zvi Cohen [b], Alva Peled [c]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287-5306, United States
[b] Material Engineering Department, Ben Gurion University, Israel
[c] Structural Engineering Department, Ben Gurion University, Israel

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A B S T R A C T

This papers addresses the disparities that exist in measuring the constitutive properties of thin section cement composites using a combination of tensile and flexural tests. It is shown that when the test results are analyzed using a simplified linear analysis, the variability between the results of tensile and flexural strength can be as high as 200–300%. Experimental results of tension and flexural tests of laminated Textile Reinforced Concrete (TRC) composites with alkali resistant (AR) glass, carbon, aramid, polypropylene textile fabrics, and a hybrid reinforcing system with aramid and polypropylene are presented. Correlation of material properties is studied analytically using a parametric model for simulation of flexural behavior using a closed form solution based on tensile stress–strain constitutive relation. The flexural load carrying capacity of TRC composites is computed using a back-calculation approach, and parameters for a strain hardening material model are obtained using the closed form equations. While the parametric model over predicts the simulated tensile response for carbon and polypropylene TRCs, predictions are however consistent with experimental trends for aramid and glass TRCs. Detailed discussion of the differences between backcalculated and experimental tensile properties is presented. Results can be implemented as average moment–curvature relationship in the structural design and analysis of cement composites.

1. Introduction

Strain Hardening Cement Composites (SHCC) have a significantly higher strength, ductility, and versatility as compared to conventional fiber reinforced concrete (FRC) and are represented by novel materials such as Textile Reinforced Concrete (TRC) [1]. TRC composites utilize innovative fabrics, matrices, and manufacturing processes and have as much as one order of magnitude higher strength, and as much as two orders of magnitude higher in ductility than fiber reinforced concrete [2,3]. Uniaxial tensile strength as high as 25 MPa, and strain capacity of 1–8% are routinely obtained [4,5]. A variety of fiber and fabric systems such as alkali resistant glass fibers (G), polypropylene (P), PVA, aramid (A), and carbon (C) have been utilized [2,6,7]. In order to fully utilize these materials. Material properties and design guidelines are needed to determine the size and dimensions, and expected load carrying capacity of structural members constructed with them.

An analytical constitutive model for backcalculation and design of TRC materials is presented in this paper. Several models have been proposed for correlation of tensile stress–strain response of fiber reinforced concrete to its flexural response. These models can be classified into different groups including cracked hinge formulations by de Oliveira e Sousa and Gettu [8], Olesen [9], fictitious crack models by Zhang and Stang [10], Kitsutaka [11], and fracture based models [12,13]. A closed-form formulation presented by Soranakom and Mobasher [14] which has recently been used by Taheri et al. [15,16], Varma and Barros [17] and Ferrara et al. [18] compares quite favorably with the inverse analysis method of Olesen [9]. This generalized approach for back-calculation of constitutive relationship from experimental data uses closed form moment–curvature equations to obtain the load

* Corresponding author. Tel.: +1 480 965 0141; fax: +1 480 965 0557.
E-mail addresses: barzin@asu.edu, barzinmobasher@gmail.com (B. Mobasher).

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deflection response of fiber reinforced concrete material [5,19]. Implementation of the inverse analysis algorithm helps in implementation of closed form moment–curvature models in non-linear finite element analysis for simulation and design of TRC composites [6,19].

This paper extends the backcalculation approach to correlate the tensile and flexural properties of thin sections of cementitious composites, measured from static mechanical tests. Warp knitted fabric alternatives considered in this study are: alkali-resistant glass (AR), polypropylene, carbon and aramid as the reinforcing yarns. In addition, a hybrid composition of aramid and polypropylene textile with yarn ratios of 25:75, 50:50, and 75:25 was also investigated. High-strength, high-modulus fibers primarily tends to increase composite strength, whereas low-modulus fibers are expected to improve toughness and ductility. The motivation was to combine yarns with different properties in one fabric to obtain synergistic effects of high strength and ductility, low cost and improved durability, as compared to traditional single type fiber composite.

2. Simplified strain-hardening fiber reinforced concrete model

The tensile behavior of TRC systems has been simplified by a constitutive model of a tri-linear strain-hardening tensile, and an elastic–perfectly-plastic compression model as derived by Soranakom and Mobasher [20,21]. By normalizing all parameters with respect to minimum number of variables, closed form derivations are obtained. Material parameters as shown in Fig. 1 are summarized as tensile stiffness E, first crack tensile strain ε_{cr}, cracking tensile strength $\sigma_{cr} = E\varepsilon_{cr}$, and post cracking modulus E_{cr} which is assigned a negative or positive value in order to simulate either strain softening or hardening materials. Constant tensile strength at the end of tension model $\sigma_{cst} = \mu E\varepsilon_{cr}$ and an ultimate tensile capacity ε_{tu}, are defined in the postcrack region.

The elastic–perfectly-plastic compressive stress–strain is characterized by a linear response which is terminated at yield point (ε_{cy}, σ_{cy}). This is followed by a plateau phase in the stress–strain response at constant compressive yield stress $\sigma_{cy} = \omega\varepsilon_{cr}\gamma E$ until reaching the ultimate compressive strain ε_{cu} as shown in Fig. 1a. Applied tensile and compressive strains at bottom and top fibers, β and λ are also defined as model variables. Using the first crack tensile strain and modulus as intrinsic material parameters, ε_{cr} and E, seven normalized variables are defined as listed in Table 1a for different fiber reinforced materials. Parameter γ represents the ratio of modulus of elasticity in tension to compression [22]. For a rectangular cross section with a width "b" and depth "d", the Kirchhoff hypothesis is applied. The normalized maximum tensile strain, β and maximum compressive strain λ are linearly related through the neutral axis parameter, k as in Eq. (1).

Table 1a
Back calculation model parameters [22,23].

Normalized tensile strain	$\alpha = \frac{\varepsilon_{trn}}{\varepsilon_{cr}}$
Constant post peak stress level	$\mu = \frac{\sigma_{cst}}{E\varepsilon_{cr}}$
Post-crack modulus	$\eta = \frac{E_{cr}}{E}$
Compressive yield strain	$\omega = \frac{\varepsilon_{cy}}{\varepsilon_{cr}}$
Tensile strain at bottom fiber	$\beta = \frac{\varepsilon_{t}}{\varepsilon_{cr}}$
Compressive strain at top fiber	$\lambda = \frac{\varepsilon_{c}}{\varepsilon_{cr}}$

$$\beta = \frac{\varepsilon_{tbot}}{\varepsilon_{cr}}; \quad \lambda = \frac{\varepsilon_{ctop}}{\varepsilon_{cr}}; \quad \frac{\lambda\varepsilon_{cr}}{kd} = \frac{\beta\varepsilon_{cr}}{d-kd} \quad \text{or} \quad \lambda = \frac{k}{1-k}\beta \tag{1}$$

Using the parameters defined in Table 1a and Eq. (1), normalized stress strain responses and toughness G_f are expressed as:

$$\frac{\sigma_c(\lambda)}{E\varepsilon_{cr}} = \begin{cases} \gamma\lambda & 0 \leqslant \lambda \leqslant \omega \\ \gamma\omega & \omega < \lambda \leqslant \lambda_{cu} \\ 0 & \lambda_{cu} < \lambda \end{cases} \quad \frac{\sigma_t(\beta)}{E\varepsilon_{cr}} = \begin{cases} \beta & 0 \leqslant \beta \leqslant 1 \\ 1+\eta(\beta-1) & 1 < \beta \leqslant \alpha \\ \mu & \alpha < \beta \leqslant \beta_{tu} \\ 0 & \beta_{tu} \leqslant \beta \end{cases} \tag{2}$$

$$G_f = E\varepsilon_{cr}^2\left[\left(\frac{\alpha-\mu-\mu\alpha}{2}\right) + \mu\beta_{tu}\right] \tag{3}$$

Parameter α represents the strain capacity normalized with respect to the first crack strain, ε_{cr}. Parameter η represents the post crack stiffness normalized with respect to the initial stiffness, E, and parameter μ represents the post tensile strength which is a strain softening parameter normalized with respect to the first crack strain ε_{cr}. By assuming linear strain distribution across the depth and ignoring shear deformations, stress distribution across the cross section at three stages of imposed tensile strain: $0 \leqslant \beta \leqslant 1$, $1 < \beta \leqslant \alpha$ and $\alpha < \beta \leqslant \beta_{tu}$ is obtained in closed form [22].

Moment capacity of a beam section according to the imposed tensile strain at the bottom fiber ($\varepsilon_t = \beta\varepsilon_{cr}$) is derived based on the force components and the centroidal distance to the neutral axis. The location of neutral axis, k, moment, M' and curvature ϕ', for a given tensile strain level β are provided in Table 2 and represents all potential combinations of interaction of tensile and compressive material models. The moment M_i and curvature ϕ_i at each stage i (corresponding to input β) are normalized with respect to the values at cracking M_{cr} and ϕ_{cr}.

$$M_i = M' M_{cr}; \quad M_{cr} = \frac{1}{6}bd^2E\varepsilon_{cr} \tag{4}$$

$$\phi_i = \phi_i'\phi_{cr}; \quad \phi_{cr} = \frac{2\varepsilon_{cr}}{d} \tag{5}$$

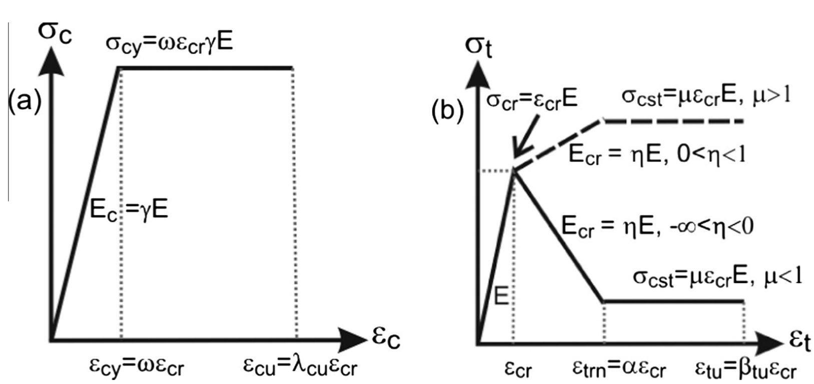

Fig. 1. Full option material models for both strain-hardening and strain-softening FRC: (a) compression model; and (b) tension model [22,23].