Backcalculation of residual tensile strength of regular and high performance fiber reinforced concrete from flexural tests

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HIGHLIGHTS

- Closed form equations for measuring tensile constitutive response from flexural tests.
- Parameters obtained from routine experimental data can be used for design of FRC elements.
- Correlation of backcalculated tensile data from flexural and direct tension tests.
- Comparison of nature of the stress distribution under the two tension and flexural tests.
- Residual tensile strength, and post crack stiffness correlated with the fiber type and content.

ARTICLE INFO

ABSTRACT

The tensile stress–strain response of a fiber reinforced concrete dominates the performance under many loading conditions and applications. To represent this property as an average equivalent response, a back-calculation process from flexural testing is employed. The procedure is performed by model fitting of the three-point and four-point bending load deflection data on two types of macro synthetic polymeric fibers, one type of steel fiber and one type of Alkali Resistant (AR) glass fiber. A strain softening tensile model is used to simulate the behavior of different FRC types and obtain the experimental flexural response. The stress–strain model for each age, fiber type and dosage rate is simulated by means of the inverse analysis procedure, using closed-form moment–curvature relationship and load–deflection response of the piecewise-linear material. The method of approach is further applied to one external data set for High Performance Fiber Reinforced Concrete (HPFRC) with two different types of steel fibers and validated by tensile test results reported. Results of back-calculation of stress–strain responses by tri-linear tensile model for all mixtures are compared and correlated with the corresponding standard method parameters used for post crack behavior characterization and a regression analysis for comparative evaluation of test data is presented.

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1. Introduction

Fiber reinforced concrete is widely used in infrastructure applications because of improved mechanical properties such as fracture toughness, ductility, durability, and crack-width control [1–5]. Steel, glass, natural, and synthetic fibers have been used over 40 years in industrial slabs, floors, and pavements to primarily reduce shrinkage and thermal cracking [6–11], reduce the required slab thickness, and increase the allowable joint spacing [12–18]. Experimental tests show that fibers increase the flexural and ultimate load carrying capacity in proportion to their volume and aspect ratio [19–24]. Fiber reinforced concrete is used in elevated slabs and water distribution infrastructure. Structural applications of fibers include but are not limited to precast structural elements [25], tunnel linings [26,27], shotcrete [28–32], offshore structures, seismic applications, thin and thick repairs [33], crash barriers, footings, and hydraulic structures [34,35]. The fibers are also added to concrete to enhance spalling resistance during exposure to high temperature [36].

The mechanical properties depend on the characteristics of the concrete matrix but also on the type and geometry of the fibers that governs their bond mechanism with the matrix [37,38]. Fibers offer increased abrasion and impact resistance as well [39,40]. The

effectiveness of short, randomly distributed fibers may be superior to other forms of reinforcement such as welded wire mesh, or rebars since the small diameter of the individual fibers ensures a more uniform dispersion, along with a far superior bond strength. Moreover, due to the reduced specific spacing, fibers strengthen the composite at the micro level by bridging the microcracks before they reach the critical flaw size [41]. Among all mechanical parameters, residual tensile strength and toughness are the most improved parameters which are a direct consequence of macro fiber bridging mechanisms across the crack surfaces [42,43]. Hybrid fiber reinforced concrete combining micro- with macro-fibers with an improved resistance against both types of cracks is also useful for a variety of applications, including thin repairs and patching [44,45].

Flexural tests are routinely done as a means of quality control and limited material properties are extracted from their results. Furthermore, the scatter and variations in these tests due to notched or un-notched samples, or the choice of control variable used in experiments, are compounded by the methods used to report the results especially in the post-peak region. For example, scatter is much smaller for synthetic fibers than steel fibers due to the higher number and more homogeneous distribution across the fracture surface [42]. Scatter is also lower for samples tested as round panel specimens tested under ASTM C1550 than ASTM C1609 beam specimens [46]. Scatter in the case of ASTM C1609 may also be attributed to the degree of rigidity of the support reactions, or frictional sliding at the supports. There is a need to better utilize the flexural test data for realistic materials property.

This paper validates a back-calculation procedure for flexural test results and obtains tension stress–strain response from a variety of tests conducted on notched and un-notched beams of different sizes, fiber types, shapes, lengths, and dosage rates. The objective is to correlate the residual strength results with empirical residual strength methods of ASTM C1609 [46], RILEM TC 162-TDF [47], and JCI-SF4 [48] which propose calculation of residual strength using simple engineering bending theory for linear elastic materials and uncracked section properties. A database used for analysis containing three internal data sets for tests conducted on polymeric, AR Glass and steel fibers at the Structural Engineering Laboratory at the Arizona State University, and one external data set for reported test results of Kim et al. [49] on High Performance Fiber Reinforced Concretes (HPFRCs). A correlation is studied between backcalculated residual strengths and various standard flexural parameters. In lieu of empirical correlation values between these parameters that are currently in use in the FRC industry, this paper provides a theoretical approach to obtain such correlation factor.

2. Materials and methods

2.1. Flexural tests

Set one of internal database consisted of two polymeric fibers of modified polypropylene, polyethylene and olefin blends, both at a dosage rate of 3 kg/m³ (5 lb/yd³). Set two consisted of AR Glass fibers at three different fiber lengths, and Set 3 consisted of one type of steel fibers at three different dosage rates. All samples were tested under flexural testing configuration and the load-deformation response in the post-peak region was measured. Physical and mechanical properties of the fibers used in the test program are presented in Table 1. The analysis section also discusses results from published work on four different mixtures of HPFRC by Kim et al. [49]. This was designated as Set 4 and included both tensile and flexural test results.

2.2. Testing program

Proportions of eight different mixtures prepared and tested under three-point bending configuration are shown in Table 2. The first letter on the samples' labels refers to the general type of fiber used, i.e. "P" in case of polymeric, "G" in case of glass fiber and "S" in case of steel fiber. The following number is the dosage of the fiber presented in kg/m³. For polymeric and steel fibers, the letter following this number refers to the type of fibers shown in Table 1, while for glass fibers; the number following this number is the length of fiber. In the results section, a final number added at the end of the labels designates the age at testing. In addition to the samples tested, one set of published HPFRC data by Kim et al. [49] was used with employed two different types of steel fibers, "H" for hooked fibers and designation "T" was introduced to refer to longitudinally twisted fibers. Subsequently, parameter "L" refers to large size of specimen with depth, width and span of 150, 150 and 450 mm, respectively, to differentiate the results from results of medium size specimens reported by Kim et al. [49].

Closed loop control flexural tests were conducted on pre-notched FRC samples of polymeric and AR glass fibers in accordance with RILEM TC 162-TDF recommendation in order to monitor post-peak response [47]. Dimensions of Set 1 Polymeric-FRC sample and Set 2 AR glass-FRC samples were 450 mm × 100 mm × 100 mm with an initial notch length of 12 mm and test span of 400 mm. Un-notched steel-FRC samples in Set 3 were tested in accordance with ASTM C1609 under four-point bending loading configuration using 510 mm × 150 mm × 150 mm specimens with a test span of 450 mm. The diameter of steel fibers used was 0.3 mm. Test setup, specimen dimensions and instrumentation are shown in Fig. 1.

Tests were performed under closed loop control with Crack Mouth Opening Deformation (CMOD) as the controlled variable for testing sets one and two, and load point deflection as the controlled variable for testing set three. Both the CMOD and deflection were measured using a Linear Variable Differential Transformer (LVDT) with a working range of 2.5 mm. In notched specimens, cracks initiated from the notch and extended up along the depth of the beam. The crack opening

Table 1
Properties of fibers used in study.

Fiber type	P-type A	P-type B	Glass (G)	Steel (S)
Base	Monofilament polypropylene/polyethylene blend	Modified olefin	Alkali resistant glass	Hooked (H)
Length (mm)	50	50	6, 12, 24	50
Density (g/cm³)	0.92	0.92	2.7	7.9
Tensile strength (MPa)	600–650	552	1724	2300
Elastic modulus (GPa)	5	10	69	200

Table 2
Mixture proportions and compressive strength of all mixtures.

Set	Mix ID	Portland cement (kg/m³)	Fly ash (kg/m³)	Silica fume (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Water (kg/m³)	Fiber type/dosage (kg/m³)	w/c	s/c	Compressive strength (MPa)
1	P3-A	475	60	15	1100	450	230	P-A/3	0.42	2	29
	P3-B	475	60	15	1100	450	230	P-B/3	0.42	2	34
2	G6-6	796	80	0	578	760	350	G-6 mm/10	0.4	0.66	41
	G6-12	796	80	0	578	760	350	G-12 mm/10	0.4	0.66	41
	G6-24	796	80	0	578	760	350	G-24 mm/10	0.4	0.66	41
3	S13-HL	380	125	0	1343	1816	242	S-HL/13	0.48	2.66	28
	S26-HL	380	125	0	1343	1816	242	S-HL/26	0.48	2.66	28
	S39-HL	380	125	0	1343	1816	242	S-HL/39	0.48	2.66	28