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# Analytical study on shear strength of macro synthetic fiber reinforced concrete beams

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ABSTRACT

Many research investigations have been performed in the past to measure and model the shear capacity of longitudinally reinforced concrete beams incorporating steel fibers (SFRC beams). Unlike SFRC, experimental and analytical studies on reinforced concrete beams with macro synthetic fibers have been limited. In this study the shear strength results from testing 23 full-scale reinforced concrete beams with macro synthetic fibers (SNFRC) are used to assess the predictions and applicability of 11 analytical shear models originally developed for SFRC beams. The results indicate that the analytical models of the fib-MC2010, RILEM, Swamy et al., Mansur et al., and Ashour et al. (Zsutty's) predict the shear strength of SNFRC beams with high accuracy. The fib-MC2010 model predicted the shear strength of slender SNFRC beams accurately, but is conservative for short SNFRC beams. The RILEM model was more conservative than the fib-MC2010 in predicting the shear strength of SNFRC beams. A statistical method was used to calibrate the original RILEM model using a set of SFRC and SNFRC test results.



## 1. Introduction

Over the past decade, there has been a more widespread use of fiber-reinforced concrete (FRC) in the building construction industry. FRC is commonly used in low risk structural elements such as slabs on ground and pavements [1] to reinforce them against shrinkage, temperature, and even external traffic and live loads. Fibers can increase the shear capacity by providing post-cracking tensile resistance across inclined cracks, resulting in higher aggregate interlock forces in a manner similar to that observed for beams with normal stirrup-type shear reinforcement [2]. Many studies have been performed in the past about using steel fibers in RC beams as flexural [3,4] and shear reinforcement [5,6]. The findings show that steel fibers can largely increase the shear capacity of reinforced concrete beams [7,8]. Unlike SFRC, there are only few studies published on the use of macro synthetic fibers as a shear reinforcement in structural concrete [9,10]. The limited research on this topic is attributed perhaps to the small increase in toughness and associated structural performance of concrete when relatively low-modulus (compared to concrete) synthetic fibers are added to concrete. Synthetic fibers, typically made of polypropylene, have primarily been used in concrete materials to control shrinkage cracking and, to a limited extent, to improve toughness and impact resistance. In recent years, however, increasing efforts have been devoted toward the development of new generation of macro synthetic fibers which impart significant toughness and ductility to the concrete. Accordingly, the application of macro synthetic fibers in the concrete industry has extended beyond shrinkage and thermal cracking control to structural applications. Large-scale testing of slabs-on-ground has demonstrated that the tested macro synthetic fiber can significantly increase the flexural and ultimate load carrying capacity of concrete slabs-on-ground relative to plain concrete slabs [11,12].

The ACI 318 Code [13] Section R11.4.6.1(f) permits the use of steel fibers as a replacement for minimum shear reinforcement in concrete members when the factored design shear $V_u$ is in the range $0.5\phi V_c < V_u \leqslant \phi V_c$, where $V_c$ is the shear strength of concrete and $\phi = 0.75$. However, the code does not permit using synthetic fibers as a shear reinforcement. One reason is that only a limited number of studies have been conducted on the shear capacity of synthetic fiber reinforced concrete (SNFRC) beams. In some of those studies synthetic fibers have been used along with steel or other types of fiber to compare their performances. Li et al. conducted experiments on small low-strength SNFRC beams reinforced with flexural rebars [9]. They tested six beams containing 1.0 vol.% polyethylene fibers. The experimental parameters

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were shear-span to depth ratio (1.0, 1.5, 2.0, and 3.0) and flexural reinforcement ratio (1.1% and 2.2%). They also tested non-fibrous beams with the same parameters for reference. The results showed remarkable improvements in shear strength due to the incorporation of fibers. Based on the test results of both macro synthetic and steel fiber reinforced concrete beams, they developed a model of shear strength prediction that incorporates splitting tensile strength, flexural strength, longitudinal reinforcement ratio, shear span, and beam depth. Noghabai tested two high-strength medium size slender beams containing 1.0% polyolefin fibers. For each beam he used a different fiber length (25 and 50 mm) [14]. The beam reinforced with the longer synthetic fibers was very tough and comparable to SFRC beams in both ductility and strength. He also devised an analytical non-linear truss model to predict the load-carrying capacity of the beams. Majdzadeh et al. tested six small normal-strength slender beams reinforced with two types of synthetic fibers at different volume fractions (0.5%, 1.0%, and 1.5%) [15]. They proposed an equation for predicting shear strength by incorporating direct shear strength [16] as an alternative to the RILEM model which is originally developed for SFRC beams. Recently, Altoubat et al. showed that the addition of a polypropylene/polyethylene based macro fiber significantly improved the shear strength and ductility of the RC beams and modified the cracking and failure behavior [17].

As mentioned earlier, shear strength of SFRC beams has been studied by many investigators in the past two decades [7]. Based on those studies several theoretical models have been developed to predict the shear strength of SFRC beams. In this study, some of the main models that can be potential candidates for implementation in design codes due to their uncomplicated nature and reported satisfactory compatibility with test results of SFRC beams are examined for their applicability for SNFRC beams. Recently new and revised models for predicting the shear capacity of SFRC beams are proposed such as the fib-MC2010, which is intended to be a model code. The method presented in this study can be used for evaluating and calibrating existing models for SNFRC, and thereby the goal of this study is to assess the predictive performance of several models, originally proposed for SFRC, to examine its applicability to SNFRC, and to present a procedure for model evaluation. The fib-MC2010 and the original RILEM formulations were specifically assessed in this study as they were formulated based on a large SFRC test database. It should be emphasized herein that for a reliable assessment of a model and deciding whether it can be used in design codes for SNFRC, data sets much larger than those presented in this study should be used.

In this study, the results obtained from testing 23 large-scale slender and short reinforced concrete beams are presented. The experimental variables include shear span to depth ratio, fiber volume fraction, flexural reinforcement ratio, and beam depth. The beams were tested under displacement-controlled center-point loading to fail in shear. The test results then were compared to the theoretical values predicted by the models. The models that best predicted the shear strength of SNFRC beams were identified. The predictive performance of the fib-MC2010 and the RILEM Models were specifically assessed for their applicability to SNFRC and a regression analysis method was used for model calibration.

## 2. Prediction models for shear strength of FRC beams

11 models proposed by different investigators were used to predict the shear strength of the beams tested in this experimental program (Table 1). These models can be divided into two categories. The models of the first category directly incorporate fiber properties that affect the mechanical performance of FRC, namely fiber aspect ratio, volume fraction of fibers and a bond factor [18]. Those properties are expressed as fiber factor, $F$:

$$F = (L_f/D_f)V_f d_f \tag{1}$$

where $L_f/D_f$ represents the fiber aspect ratio, $V_f$ is the fiber volume fraction, and $d_f$ is the fiber bond factor. Narayanan and Kareem-Palanjian performed a large series of pullout tests to determine the fiber bond factor [18]. Based on their experiments, the values of 1.0, 0.75, and 0.5 were selected as $d_f$ for hooked-end, crimped, and straight steel fibers, respectively. Some of the models (the model of Swamy et al. presented in this study [19]) incorporate the effect of fiber orientation on the post-cracking tensile strength, and therefore the shear capacity of FRC. The readers are referred to the articles by Swamy et al. [19] and Khuntia et al. [20] for discussions on the effect of fiber orientation and the quantification of this effect. The models of the first category which are used in this study are those of Mansur et al. [21], Narayanan and Darwish [22], Ashour et al. [23], Swamy et al. [19], and Imam et al. [24]. In the second category, fibers mechanical properties are indirectly accounted for through material strength characteristics like splitting tensile strength, modulus of rupture, equivalent flexural strength, and residual tensile strength factors. The examples of this category are the models of Sharma [25], Li et al. [26], RILEM [27], and fib-MC2010 [28].

Among the 11 models presented in Table 1, the fib-MC2010 model and the initial RILEM model were developed based on a large set of SFRC beam test data and thus are receiving wide acceptance in the research community, particularly the fib-MC2010 model. Further details of these models are presented in the following sections.

### 2.1. The model of fib-MC2010

According to the fib-MC2010 [28], the shear strength of a longitudinally reinforced FRC concrete beam, $v_{Rd}$, is obtained by adding the contributions of FRC, $v_{Rd,F}$, and steel stirrups, $v_{Rd,s}$:

$$v_{Rd} = v_{Rd,F} + v_{Rd,s}, \tag{2}$$

where

$$v_{Rd,F} = \frac{0.18}{\gamma_c}.k.\left[100\rho_l.\left(1 + 7.5\frac{f_{Ftuk}}{f_{ctk}}\right).f_{ck}\right]^{1/3} + 0.15\sigma_{cp}. \tag{4}$$

In this equation, $d$ is the effective depth of the cross section; $b_w$ is the width of the cross section; $\gamma_c$ is a partial safety factor for concrete; $\rho_l$ is the longitudinal reinforcement ratio and $k$ is a factor related to the size effect that can be calculated as follows,

$$k = 1 + \sqrt{200/d} \leqslant 2. \tag{5}$$

$f_{ctk}$ and $f_{ck}$ are, respectively, the characteristic values of the tensile and compressive strength of the concrete matrix, and $f_{Ftuk}$ is the characteristic value of the ultimate residual tensile strength of FRC that is determined by the following equation:

$$f_{Ftu}(w_u) = f_{Fts} - \frac{w_u}{2.5}.(f_{Fts} - 0.5.f_{R3} + 0.2.f_{R1}) \geqslant 0. \tag{6}$$

In this equation, $w_u$ = 1.5 mm, and $f_{Fts} = 0.45f_{R1}$; assuming the linear post-cracking behavior constitutive model as described in the fib-MC2010 [28]. The characteristic values of the tensile and compressive strength for the concrete matrix $f_{ctk}$ and $f_{ck}$ are calculated as follows

$$f_{ck} = f_{cm} - 8 \tag{7}$$

$$f_{ctm} = 0.3f_{ck}^{2/3} \tag{8}$$