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Shear resistance of steel fiber-reinforced concrete beams without conventional shear reinforcement on the basis of the critical shear band concept

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ABSTRACT

Recently, a concept to estimate the shear capacity of slender reinforced concrete beams without stirrups by examining the principal tensile stress within the shear span was introduced. Considering the existence of both the concrete normal stress and the shear stress in the tension zone, the calculated principal tensile stress is in excess of the concrete tensile strength in a narrow band in this concept. In this band, damage in form of micro-cracking is assumed. The critical shear crack is formed by coalescence of micro-cracks when the damaged band reaches a critical size. By limiting the tensile cracking in the shear band, steel fibers can postpone the critical shear crack development and, thus, enhance the shear resistance in this concept. This paper presents an extension of this method to estimate the shear capacity of slender steel fiber-reinforced concrete beams without conventional shear reinforcement. The proposed method is shown to properly estimate the shear resistance of a large set of available test data, being able to account for most influencing parameters.

1. Introduction

Shear failure of slender reinforced concrete (RC) beams without shear reinforcement is brittle and usually occurs without warning. Considering the brittle nature of plain concrete behavior in tension, several researchers [1,2] suggested that shear failure occurs when the principal tensile stress within the shear span exceeds the tensile strength of concrete. This view agrees with the view commonly held in the past when the problems of shear and diagonal tension in RC members without shear reinforcement were usually incorporated, e.g. by ACI-ASCE Committee 426 [3]. Until very recently, the tensile strength of concrete was still considered to play a decisive role in the shear resistance of RC members without shear reinforcement (V_{ct}) in the German Code DIN 1045-1 [4], where the index “ct” accounts for the concrete tensile strength [5,6]. Although the equation included in this code was derived semi-empirically from test results, this view aims to represent the brittle shear failure of slender RC beams due to the brittle behavior of concrete in tension.

Over the past four decades, there has been interest in studying the potential of using steel fiber-reinforced concrete (SFRC) to improve the performance of RC beams. Fiber reinforcement of cement matrices enhances the post-cracking strength properties of the hardened composite by controlling the tensile cracking [7]. Considering that the shear failure of RC beams is controlled by tensile behavior of concrete, the addition of steel fibers can thus improve the shear performance of RC beams without shear reinforcement. This effect has been confirmed by a large number of studies, as shown in a review by Minelli [8] or in a database constructed by Parra-Montesinos [9]. In these studies, the effect of most parameters that have an influence on the shear resistance of RC beams as well as the fiber content and characteristics have been intensively investigated in small and medium size specimens. Recently, several investigations with large-scale specimens to study the size-effect in SFRC beams have been carried out by Dinh et al. [10], Shoaib et al. [11] and Minelli et al. [12]. These studies are of great significance in investigating on the shear behavior of SFRC beams, since they have achieved good specifications for most influencing parameters.

In the context of the modeling aspect, existing models for predicting the shear resistance of SFRC beams are usually based on relevant models for RC beams. Since available shear models for RC beams differ primarily in the computation of components provided by different shear-carrying mechanisms, a large number of equations to predict the shear resistance of SFRC beams are known. Besides a generation of plastic models [13,14], according to Aoude et al. [15], existing models for SFRC beams can be roughly classified in two categories by modeling the effect of steel fibers, i.e. separation of shear contribution of fibers and improvement of the concrete contribution.

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Notation

a	shear span
b_w	web width
d	effective depth of beam
$d_{b,crit}$	critical width of shear band for plain concrete
$d_{b,crit,frc}$	critical width of shear band for fiber concrete
d_f	fiber diameter
f_c	compressive strength of concrete
f_{ct}	tensile strength of concrete
f_{Ftu}	residual tensile strength of SFRC
G_F	fracture energy of concrete
l_f	fiber length
M_{cr}	cracking moment of the cross-section
v_f	fiber volume fraction
V_{frc}	shear resistance of SFRC beam without shear reinforcement
n	modular ratio for reinforcement steel $n = E_s/E_c$
s_{rm}	crack spacing of primary cracks
x	cracked concrete section neutral axis depth
x_0	distance from the critical shear crack to the support
$x_{control}$	distance from the control section to the support
x'	distance from the peak of the concrete tensile stress to the neutral axis
x''	height of the region with softening of concrete in the tension zone
w_k	crack opening of the primary flexural cracks
ε_{ct}	strain of concrete by reaching the tensile strength
ε_s	strain in longitudinal reinforcing bar
ρ_s	reinforcement ratio for the flexural reinforcement
σ_{xm}	average normal stress of concrete within the critical width of the shear band

In the greater number of shear equations for SFRC beams [16–19], the vertical projection of the residual tensile stress distributed along the inclined shear crack σ_{tu} is considered as the shear resistance provided by steel fibers V_{fib}, as illustrated in Fig. 1. This component contributes to the shear resistance of a beam in addition to the shear at diagonal cracking V_c. Thus, the shear resistance of a SFRC beam without stirrups V_{frc} can be expressed as

$$V_{frc} = V_c + V_{fib} \tag{1}$$

There has been an attempt to use shear models included in design provisions for determining the concrete contribution V_c. Mansur et al. [16] recommended the proposal of ACI-ASCE Committee 426 [3] which was included in ACI-318 Code [20] for computing the diagonal tension cracking load V_c. Similarly, the equations of RILEM Committee 162-TDF [21] and the German Guideline [22] are based on the shear model for RC beams of EC2 [23]. It is well recognized that the model in ACI-318 cannot represent the size-effect, while the equation in EC2 cannot describe the effect of shear span-to-depth ratio (a/d-ratio) on the shear resistance of RC beams. The models for SFRC beams, thus, inherit these shortcomings from the original models for RC beams. Recently, Foster [24] and Aoude et al. [15] developed similar shear models for SFRC beams based on the simplified modified compression field theory (SMCFT) [25] through the addition of the fiber component to the shear resistance of RC beams.

Besides differences in the reinforced concrete contribution, some variations can be found in the calculation of the fiber contribution among models of this type. Mansur et al. [16], Foster [24] determined the residual tensile strength of concrete directly from the uniaxial tensile test, while Dinh et al. [26] and Minelli et al. [12] used the results from three- or four-point bending tests. Because no data were available with regard to either uniaxial tension or flexural performance of SFRC for historical tests, the validation of some shear models for SFRC beams was done using the pull-out strength described by Swamy and Al-Ta'an [7]. The pull-out strength of FRC is influenced significantly by the bond and the fiber factor $v_f(l_f/d_f)$, where v_f is the fiber volume fraction, l_f and d_f are the fiber length and diameter, respectively.

In models of the second category [8,27–30], fibers are considered to directly improve the concrete contribution. The best known is the model of Minelli [8], which has been included in the *fib* Model Code 2010 [31]. This model was derived by an adaption of the empirical equation included in EC2 [23] for RC beams without stirrups. Steel fibers are considered to have a similar effect as longitudinal reinforcement and, thus, improve the shear capacity. While the *fib* Model Code 2010 [31] adopted the SMCFT [25] for RC beams, the modification of the SMCFT for SFRC beams proposed by Foster [24] was considered to be not fully validated and was not included. The inconsistency by adopting separated models with different mechanical roots for RC beams and SFRC beams in the *fib* Model Code 2010 represents the current situation in research on shear resistance of SFRC beams. This creates the need for further development of more rational design methods.

Recently, Tue et al. [32], Tung and Tue [2] introduced a new concept to describe the formation of the critical shear crack, referred to as the critical shear band concept in the followings, and a corresponding procedure for shear resistance of slender RC beams without stirrups. The critical shear crack formation is characterized by the coalescence of micro-cracks in a band with principal tensile stress exceeding the concrete tensile strength when the width of this band reaches a critical value. Considering the ability of steel fibers for limiting the tensile cracking and damage potential in the shear band, this concept is capable of accounting for an enhancement of the shear capacity in SFRC beams.

This paper presents an extension of the method to estimate the shear capacity of slender SFRC beams based on the critical shear band concept, which is briefly summarized in the following section. The ability of steel fibers for limiting the failure potential in the shear band is modeled by enlarging the critical width of this band, the effects of fibers on the primary crack spacing and the length of uncracked region are also considered. The presented method is limited to strain-softening fiber concrete.

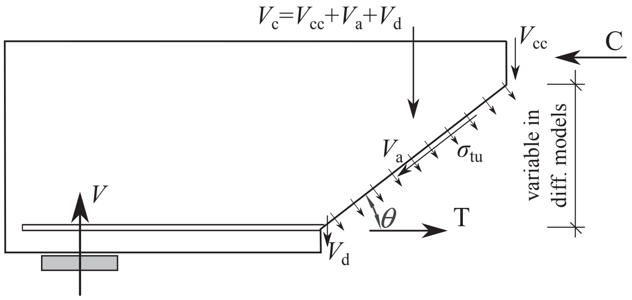

Fig. 1. Contribution of fibers to shear resistance of FRC beams without stirrups.