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Shear strength prediction for steel fiber reinforced concrete beams without stirrups

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ABSTRACT

This study proposes a theoretical approach based on modified compression field theory to predict the shear strength of steel fiber-reinforced concrete (SFRC) beams without stirrups. The tensile contribution of the steel fibers is considered in the tensile stress–strain constitutive equations, which take into account the distribution of the fibers. The proposed strength model is verified by comparing it with 139 shear failure tests previously conducted on SFRC and reinforced concrete beams without stirrups. The influences of concrete strength, fiber volume, shear span-to-depth ratio, and longitudinal steel ratio on predicted shear strength are also discussed. Comparisons between the predicted and experimental results show that the proposed model can estimate shear strength accurately.

1. Introduction

Previous studies have shown that adding steel fibers to concrete increases tensile strength, post-cracking toughness, and ductility of concrete [1,2]. One of the most important functions of steel fibers in concrete is transferring stress across cracks, thus providing post-cracking diagonal tension resistance to RC beams. Fibers have been found to control crack development, prevent large crack widths, increase ultimate shear strength and stiffness, and reduce deflections of concrete beams, thus also enhancing aggregate interlock. Furthermore, using steel fibers transforms the failure mode from brittle shear into ductile flexural [3–8].

Numerous experimental and theoretical investigations on shear problems of various fibrous concrete beams without transverse reinforcement have been conducted during the past three decades [3–29]. These studies have indicated that adding fibers significantly improves the shear capacity of beams. Based on the experimental results, numerous researchers have proposed equations to predict the ultimate shear strength of SFRC beams. A summary of several models is presented in Table A1 in the Appendix. In the existing models, the idea that the contribution of fibers and concrete in the shear strength of steel fiber reinforced concrete (SFRC) beams is independent is still prevalent today. On the other hand, other studies hold the view that the contribution of fibers and concrete in shear strength is coupled.

Mansur et al. [6] performed twenty-four simply supported beams under two symmetrical point loads and proposed an equation to calculate the ultimate shear at failure. In the model the effect of fibers were included by considering a uniform stress block of average stress along the tension crack, providing good predictions of the ultimate strength. However, for beams with short shear spans, the predicted shear capacities were highly conservative. Sharma [4] performed seven tests on SFRC beams and proposed an equation to calculate the ultimate shear at failure. The proposed equation is a function of the concrete tensile strength and the shear span-depth ratio. The equation was validated with 41 other tests on SFRC beams. However, the equation ignored some important parameters that contribute to the shear strength, such as fiber volume, aspect ratio, and tensile reinforcement ratio. Narayanan and Darwish [9] proposed the cracking and ultimate shear equations for SFRC deep and slender beams based on 33 tests on SFRC beams. The proposed equations considered the bond stresses in the fiber matrix. The combined effect of fiber volume and aspect ratio is also considered as fiber factor. Kwak et al. [10] proposed two empirical equations for ultimate shear strength of SFRC deep and slender beams based on the Zsutty's equation [11], considering the anchoring action in addition to fiber factor. Swamy et al. [12] performed

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Nomenclature

l_f	fiber length
d_f	equivalent diameter
ρ_x, ρ_z	the reinforcement ratios in the longitudinal and transverse direction
f_c'	cylinder compressive strength
d_a	maximum aggregate size
f_{sx}, f_{sz}	average stresses in the longitudinal and transverse reinforcement
f_1	average tensile stress
f_2	average compressive stress
θ	inclination of the diagonal compressive
v	shear strength
ε_x	average longitudinal strain
ε_z	average transverse strain
ε_2	principal compressive strain
ε_1	principal tensile strain
v'_{ci}	shear stress on the crack face for SFRC
v_{ci}	shear stress on the crack face for RC
w	average crack width
s_θ	average crack spacing
s_x, s_z	indicators of the crack control characteristics of the *x*-reinforcement and the *z*-reinforcement
σ_f	stress transfer capability perpendicular to the crack
a	the aspect ratio ($a = l_f/d_f$. l_f, d_f represent the length and diameter of fibers, respectively)
τ_f	the average bond strength
V_f	the volume fraction of fibers
ω_2	the degree of planar orientation
w	the average crack width
f	the coefficient of friction between concrete and fiber sheared over the crack edge
P_f	average value of the load carried by the fibers that intersect the crack
N_A	number of fibers per unit of area for 3D $\left(N_A = \frac{\pi}{2}\frac{V_f}{d_f^2}\right)$
α	arbitrary angle between the loading direction and the fiber
f_{ci}	compressive stress on the crack surface
v_f	load component of P_f parallel to crack ($v_f = \sigma_f/(1+f)$)

an experiment program on SFRC beams and proposed a shear equation considering the post-cracking tensile strength of fiber concrete. Li et al. [13] proposed two equations to predict the shear strength of deep and slender SFRC beams. In their model, both the flexural and splitting strengths were important in predicting the ultimate shear strength. Khuntia et al. [14] proposed a simple equation for shear equations for SFRC beams also considering the post-cracking tensile behavior of FRC beams. They added one additional term in the ACI building code equation to include the contribution of fibers, which was derived from the equilibrium condition of the forces in the diagonal crack, assuming 45° for the shear cracking angle. The proposed model can reflect arch action, fiber volume fraction, fiber orientation, and effective length of fiber at crack. Dinh [15] proposed a simple model to estimate the shear strength of SFRC beams without stirrup reinforcement. In their approach, actual tension stress distribution is replaced by an equivalent uniform tensile stress with the same tensile force resultant. The contribution of fiber reinforcement to the shear strength of the beam is directly linked to the material performance obtained through a standard ASTM 1609 four-point bending test. Yakoub [16] developed two equations to predict the contribution of steel fiber to the shear strength of SFRC. These equations were used to modify the CSA A23.3-04 general shear design method and the equations of Bažant and Kim [17]. Yakoub introduced the contribution of steel fiber to the shear strength of SFRC by considering fiber distribution. Slater et al. [18] proposed six different empirical equations based on regression analysis. The equations were developed to predict the shear strength of SFRC beams based on span-depth ratio, concrete compressive strength and fiber shape. However, it is not desirable in the design perspective to use six different equations to predict the shear strength. Shahnewaz and Alam [19] carried out a parametric study to evaluate the contribution of different parameters on the shear strength of SFRC beams. They developed several analytical equations to predict the shear strength of SFRC beams by genetic algorithm (GA). Compared with previous test results, the proposed equations produced less scatter with high accuracy. However, the proposed shear equations did not attempt to model the physical reality of actual resisting shear mechanisms in SFRC beams due to the complex nature.

In the previous studies mentioned above, most models agree well with the test results from which it is derived, but the model does not show good agreement with the other test results. The main reason for that is most existing shear strength models for treating shear still rely on empirical or semi-empirical formulas because of the difficulty in understanding the complex shear transfer mechanism. However, several recent approaches, such as the models of plasticity theory [30] or modified compression field theory [31,32] (MCFT), can be regarded as rational because they reveal the physical mechanisms involved. Until now, however, the proposed shear strength model based on MCFT just adds the contribution of steel fibers to the shear strength provided by the RC beams. Such as the equations suggested by Yakoub [16], in which the shear strength provided by concrete was given by the CSA A23.3-04 (2004) [33] shear strength code. While the fiber contribution was a separate part, which was determined by compressive strength, the aspect ratio, volume fraction and fiber geometry, without explaining how the bridging effect of fiber transfer the shear stress for the SFRC beam.

The current study proposes a model based on MCFT to estimate the ultimate shear strength of SFRC. Fiber action is introduced into cracked concrete, and the cracked SFRC is regarded as a new material. Compared with previous models, the proposed model considers the bridging effect of fiber based on equilibrium equations. The study clarifies the physical reality of actual resisting shear mechanisms in SFRC beams. The important parameters that affect the shear strength were all considered though mechanical model. The proposed model examines the feasibility of applying MCFT to assess shear resistance of SFRC beams without stirrups rationally. The model is then applied to existing test results available in literature to evaluate its accuracy. The results show that the proposed strength model accurately predicts the test results of SFRC beams without stirrups.

2. Review of previous experimental data

In the past few decades, a large number of experimental studies have been conducted to investigate the shear behavior of SFRC beams. A complete list of the tests used, along with their references, is presented in Table A1. This list summarizes the details of the test specimens and the results of previously performed experiments to determine the effects of steel fibers on the shear behavior of concrete beams, which have been used for the shear