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Shear behaviour of steel fibre reinforced self-consolidating concrete beams based on the modified compression field theory

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ABSTRACT

A series of steel fibre reinforced self-consolidating concrete (SFRSCC) beams have been tested to investigate the influence of steel fibres and the combined effect of fibres and stirrups on the deflection and cracking, ultimate loads and failure pattern. The experiment indicates that the shear strength increases clearly with the increasing of fibre content. The combination of steel fibres and stirrups demonstrates a positive composite effect on the ultimate load, ductility and failure pattern of concrete beam. This study also examines the feasibility of applying the modified compression field theory (MCFT) for the suitable assessment of shear resistance in fibre and steel rebar reinforced self-consolidating concrete beams. For fibre reinforced concrete member, a theoretical method is proposed based on the MCFT. The proposed ultimate shear capacity model was verified by the comparison with different test results.

1. Introduction

Concrete has low tensile strength and fails in a brittle manner. If fibres are added to the classical components of concrete, then the steel fibre reinforced concrete (SFRC) can show higher toughness under static loading, such as tension, bending and shear. Steel fibres in the concrete can also enhance the mechanical properties, ductility and energy absorbing capacity under seismic, impact and blast loading [1]. One of the most important functions of steel fibres in concrete is the ability to transfer stresses across the cracked section, providing to concrete a residual strength, which magnitude depends on the fibre, matrix and fibre–matrix properties. The application of fibre reinforced self-consolidating concrete (SFRSCC) is one of the major part of special SCC. To increase the efficiency of steel fibres in concrete matrix, SFRSCC combines the benefits of SCC in the fresh state and shows some improved performances in the hardened state of steel fibre reinforced concrete (SFRC), especially the bond property between the fibre and the concrete matrix [2]. The most efficient applications of SFRSCC are those where the fibres can replace the conventional reinforcement. Some examples are applications in industrial floors, support of tunnellings, beams [3–6]. Nonetheless, the structural use of SFRSCC in the concrete industry has not yet been fully achieved because a design procedure that considers the randomly distributed discrete fibre behaviour across cracks in a rational manner is very rare.

Previous studies of shear carried out for structural applications of fibre reinforced concrete include slender and deep beams, with or without transverse reinforcement [7–15]. These studies indicate that the addition of fibres can greatly improve the shear capacity of beams. Fibres can be used either to boost the shear capacity or to replace, in part, the vertical stirrups in conventional reinforced concrete structural members. Although numerous experimental and theoretical investigations on shear problems of various fibrous concrete beams have been made during the past three decades, few are concerned with SFRSCC beams. Test data available on the reinforcing effect of fibres in the self-consolidating concrete members failing in shear are rather limited [16,17]. Most design code methods in treating shear still rely on empirical formulas, although some recent approaches, such as the plasticity theory or the modified compression field theory (MCFT), can be regarded as rational in the sense that they are capable of providing physical significance [13,18,19].

This study examines the feasibility of applying the MCFT for the rational assessment of shear resistance in steel fibre reinforced self-consolidating concrete beams, while providing experimental data to support the theory proposed, as well as to extend the current experimental database. An experimental program was therefore conducted to study the shear behaviour of SFRSCC beams containing longitudinal bars and vertical stirrups. Moreover, the hybrid effect of steel fibres and stirrups on the mechanical behaviour of beams was also studied.

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Nomenclature

α	the aspect ratio
l_f	fibre length
d_f	equivalent diameter
ρ_s	the longitudinal reinforcement ratio
ρ_v	stirrup ratios
a/d	shear span-to-depth ratio
f'_c	cylinder compressive strength
d_a	maximum aggregate size
f_f	load of a single fibre transferred intersects at crack
σ_f	load component of a single fibre transferred perpendicular to crack
v_f	load component of a single fibre transferred parallel to crack
SFRSCC	steel fibre reinforced self-consolidating concrete
SF40-240	steel fibre reinforced self-consolidating concrete beams with 40 kg/m^3 steel fibre content and a 240 mm spacing of stirrup
b_w	width of the beam cross section
d_v	effective shear depth, taken as the greater of 0.9 d or 0.72 h
d	effective depth of the beam cross section
h	depth of the beam cross section
d_m	the average of final diameter in slump flow test
f_{yl}	yield stress of longitudinal reinforcement
f_{yst}	yield stress of stirrup
T_{500}	the time for concrete to reach the 500 mm spread circle in the slump test
T_{200}, T_{400}	time taken for the mixture to reach 200 mm and 400 mm in the L-box test
H_2/H_1	the blocking ration in the L-box test
F_{cr}	shear cracking load
F_u	the ultimate load

2. Proposed methods based on MCFT

The MCFT [20] is a further development of the CFT (compression field theory) that accounts for the influence of the tensile stresses in the cracked concrete. It was developed by observing the response of a large number of reinforced concrete (RC) elements loaded in pure shear or shear combined with axial stress. The relationship of the MCFT can be used to predict the shear strength of a beam subjected to shear, moment and axial load. The simplified MCFT for calculating shear strength of RC elements was also proposed [21,22]. In these models, the cracked concrete is treated as a new material with its own stress–strain characteristics. It is interesting to note that the fibre reinforced concrete is more suitable than plain concrete for the application of MCFT, due to its flatter stress–strain relationship in the post-peak range in compression and in tension than that of plain concrete, the studies of shear problems reflecting this are absent. The contribution of fibres to the shear capacity of SFRC can be taken into account based on the MCFT.

Failure of the RC element may be governed not by average stresses, but rather by local stresses that occur at a crack [20,23]. In checking the conditions at a crack, the actual complex crack pattern is idealised as a series of parallel cracks, all occurring at angle θ to the longitudinal reinforcement and space a distance S_θ apart. For a free-body diagram of part of fibre reinforced concrete element, Fig. 1 compares the calculated average stresses (Plane 1 in Fig. 1a) with the actual local stresses that occur at a crack (Plane 2 in Fig. 1b). The critical crack direction is assumed normal to the principal tensile strain direction. While the calculated average shear stress on Plane 1 is zero, there may be local shear stresses on Plane 2.

As the applied external stresses are fixed, the two sets of stresses shown in Fig. 1a and b must be statically equivalent. Assuming a unit area for both Plane 1 and Plane 2, the requirement that the two sets of stresses produce the same force in the z-direction is

$$\rho_{sz} f_{sz} \cos\theta + f_1 \cos\theta = \rho_{sz} f_{szcr} \cos\theta - f_{ci} \cos\theta + v_{ci} \sin\theta + v_f \sin\theta + \sigma_f \cos\theta \quad (1)$$

At high loads, the average strain in the stirrups ε_z will typically exceed the yield strain of transverse steel. In this situation, both f_{sz} and f_{szcr} will equal the yield stress in the stirrups, and then we can get:

$$f_1 = (v_{ci} + v_f) \tan\theta + \sigma_f \quad (2)$$

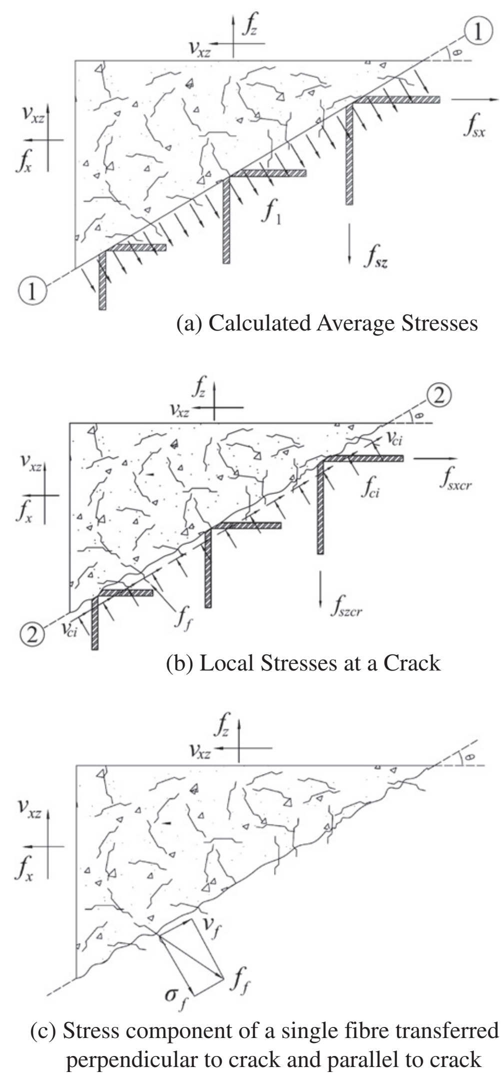

Fig. 1. Comparison of local stresses at a crack with calculated average stresses of SFRC and stress state of a single fibre.