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A crack-shear slip model of high-strength steel fiber-reinforced concrete based on a push-off test

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HIGHLIGHTS

- Crack-shear slip model of high-strength steel fiber-reinforced concrete is proposed.
- Good agreement between the model and experimental results was observed.
- Direction of concrete flow and stirrups shows combined effect on shear strength.

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ABSTRACT

This paper presents the shear behavior and a crack-shear slip model of high-strength steel fiber-reinforced concrete based on a push-off test. The parameters were the compressive strength of the concrete, steel fiber volume fraction, stirrup ratios, angle between the shear plane-flow direction in shear flow and angle between the shear plane-stirrups. The test results indicated that the shear strength increased by approximately 1.5–2 times due to the presence of steel fibers and the ductility effectively increased when using steel fibers and stirrups. The angle of the shear plane-flow direction in shear flow and the angle of the shear plane-stirrups significantly affected the shear strength. In this paper, a crack-shear slip model for high-strength steel fiber-reinforced concrete is proposed using the tri-linear relationship. The results calculated from the model corresponded with the test results.

1. Introduction

High-strength steel fiber-reinforced concrete is widely used. Previous research showed that the strength and ductility of fiber-reinforced concrete increased due to the presence of steel fibers [1–5] because of the bridging effect of steel fibers, which helps to resist the opening of cracks. When cracks initiate in normal strength concrete, shear force transfers across the crack by aggregate interlock [6] and is resisted by stirrups [7] and steel fibers [8]. On the other hand, cracks in high-strength concrete pass through aggregate, leading a flat crack plane. The aggregate interlocking effect therefore decreases. Steel fibers play an important role in resisting shear force, even on the flat crack plane. In the last decade, shear transfer models have been proposed using different theories, such as modified compression field theory [9], disturbed stress field model [10] and shear model based on push-off test [2,11–14]. Crack slip (δ) can be predicted from the shear stress (τ) [6], crack width (w) [12,15,16], maximum aggregate size and compressive strength of concrete [9]. However, the shear behavior of steel fiber-reinforced concrete is different from conventional concrete [1,2,11,17]. The load carrying capacity and crack propagation of steel fiber-reinforced concrete depend on several parameters, such as the volume fraction of steel fibers [4] and the fiber orientation [18,19]. Because the fiber orientation is difficult to control, the shear transfer model of high-strength steel fiber-reinforced concrete is difficult to predict. In addition, stirrups also affect the shear strength [8].

The objective of this paper is to propose a crack-slip model of high-strength steel fiber-reinforced concrete. The direct shear push-off test was performed. The compressive strength of concrete, the amount of steel fibers, the number of stirrups, the crack plane-stirrup angle, and the crack plane-flow direction in shear flow were considered as parameters in this paper. The shear behavior of high-

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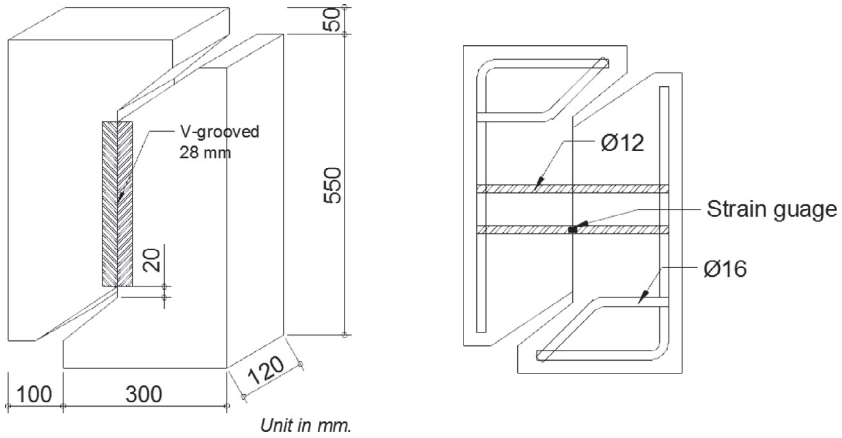

(a) Dimension (b) Detail of reinforcement

Fig. 1. Details of the specimen.

Table 1
Mix proportion of high-strength steel fiber-reinforced concrete.

Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Silica fume (kg/m^3)	Superplasticizer (kg/m^3)	Steel fiber (kg/m^3)	Volume fraction of fibers (%)
975	210	1090	73	19	62.8	0.8
975	190.7	1068	73	19	125.6	1.6

strength steel fiber-reinforced concrete is discussed. The proposed model can be used for numerical analysis.

2. Experimental program

2.1. Specimens

The specimens are 400 mm wide, 600 mm high and 120 mm thick, as shown in Fig. 1. Deformed steel bars with a diameter of 12 mm were used as the shear reinforcement. Sixteen millimeter deformed bars were placed in the specimens to improve the strength at the loading point [6].

2.2. Materials

Two compressive strength of concrete (80 MPa and 120 MPa) were used. The mix proportions are summarized in Table 1. The mix proportions provide the compressive strength of 120 MPa at 28 days. Specimens with target compressive strength of 80 MPa were tested at 3 days after casting. The 12-mm and 16-mm deformed bars were placed in the specimens. The yield strength of 12-mm and 16-mm deformed bars was 480 MPa and 430 MPa, respectively. Table 2 presents the properties of the steel fibers used in this paper.

2.3. Casting method

To study the effect of fiber orientation, the direction of the fibers was controlled. Two casting methods were applied: the flowing method (Fig. 2) and the fall method (Fig. 3). The direction of the fibers can be controlled by the flowing method. Fig. 4 presents the process to fabricate the specimens. After mixing concrete in a mixer, the concrete freely flowed on a steel rail into the formwork. The width and length of the steel rail was 800 mm and 1500 mm, respectively. Concrete flowed into the formwork until the thickness of the concrete reached 120 mm. Then, the specimen frame was pressed on fresh concrete to fix the direction of the fibers in the specimen. After casting, the concrete outside the specimen was removed. It is assumed that the flow direction in shear flow is the same as the flowing direction of the concrete. On the other hand, casting by the fall method (Fig. 3) results in a random orientation of fibers in the specimen. In this case, the concrete is poured into the formwork.

Table 2
Steel fiber properties.

Length (mm)	Aspect ratio	Shape	Minimum tensile strength (MPa)
13.0	81.25	Straight	>2000

2.4. Experimental cases

Thirty-one specimens were prepared. The experimental program was divided into 4 series, as presented in Table 3. The variables were the compressive strength of concrete (f'_c), the volume fraction of the fibers (ρ_f), the stirrup ratio (ρ_R), the angle between the crack plane-flow direction in shear flow ($_f$) and the angle between the crack plane-stirrups ($_R$).

2.4.1. Series 1

There are no steel fibers in this series, and the compressive strength is 120 MPa. The stirrup ratios are 1.2% and 2.4%. Fig. 6(a) shows the specimens in series 1. The crack plane-stirrup angles are 90°, 60° and 45°. The crack plane-stirrup angle = 30° cannot be set due to the shape of the specimens.

2.4.2. Series 2

In this series, the volume fraction of fibers is 0.8%, and the compressive strength is 120 MPa. The stirrup ratio, crack plane-flow direction in shear flow angle (θ_f) and crack plane-stirrup angle (θ_R) are varied, as summarized in Table 3. The casting direction is shown in Fig. 6(b). The stirrups are always perpendicular to the flow direction of the concrete. The flow direction in shear flow is