Engineering Structures 176 (2018) 812–824

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Bond behavior between basalt fibres reinforced polymer sheets and steel fibres reinforced concrete

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ARTICLE INFO

Keywords:
Basalt fibre reinforced polymer (BFRP)
Steel fibre reinforced concrete (SFRC)
Debonding

ABSTRACT

Bonding behavior between FRP and Steel fibre reinforced concrete is not well studied. This study experimentally investigates the interfacial bond behavior between basalt fibre reinforced polymer sheet (BFRP) and steel fibre reinforced concrete (SFRC). Short steel fibres with four volume fractions were used to investigate the interfacial bond behavior of BFRP-SFRC as the mechanical properties of the concrete substrate (i.e. compressive strength and tensile strength) can be improved by adding steel fibres. The effects of volume fraction on the bond strength, effective bond length, local slip at the peak shear stress, and interfacial bond-slip relationship are evaluated and discussed. The experimental results showed that the debonding process becomes more ductile as the debonding plateau in the load and displacement curves has been significantly extended. Findings from the present tests show that the specimens with steel fibres of 0.25%, 0.50% and 1.0% experienced significant increase in the peak interfacial shear stress up to 31%, 53%, and 76% over the control specimen without steel fibres, respectively. In addition, the analytical bond strength models and interfacial bond-slip models, incorporating the effect of short steel fibres, are proposed.

1. Introduction

Normal concrete as the most common construction material is brittle and has very low strain capacity and resistance to tension and bending. Various short fibres such as natural, synthetic and steel fibres have been used to reinforce normal concrete. Since 1960s steel fibres reinforced concrete (SFRC) has been developed and used in civil engineering applications, especially for high-rise and long-span structures [1–3]. Adding steel fibres reinforced concrete (SFRC) has superior resistance to cracking and crack propagation due to the fact that steel fibres composites increase tensile strength at both pre-cracking and post-cracking stage [4]. As compared with normal concrete, SFRC is a ductile material as compared with normal concrete and the ductility can increase energy absorption capacity to resist seismic, impact and blast loads [5]. During service life of SFRC structures, structural strengthening is needed with the increasing requirement of load-carrying capacity [5–8]. Fibres reinforced polymer (FRP) is a popular strengthening material for reinforced concrete (RC) structures due to its low weight, high stiffness and strength to weight ratios [9]. Aramid FRP (AFRP), glass FRP (GFRP), and carbon FRP (CFRP) are the most common FRP composites. Recently, Basalt FRP (BFRP) has been widely used because it has not only excellent mechanical properties but also a competitive price [10]. For the FRP strengthened RC under different loading conditions, debonding is a dominant failure mode that is induced by a localized flexural or shear-flexural cracks formed in the concrete [11–15]. The debonding failure limits the strain capacity of FRP since it occurs at lower FRP strain than its ultimate strain [16]. Furthermore, the debonding failure cannot be prevented in FRP-strengthened RC structures due to the fact that the localized crack easily causes the debonding along the interface between FRP and plain concrete (PC) [17]. Therefore, adding fibres in RC members can improve structural performance by limiting microcracks and delaying FRP debonding.

In literature, a number of studies have investigated the flexural and shear behavior of FRP strengthened RC beams [12,18–20] and FRP strengthened fibres reinforced concrete (FRC) structures [6–8,17,21,22]. Benvenuti and Orlando [6] conducted finite element analysis on the FRP-strengthened SFRC beams and found that failure of beams was mainly dependent on the content of steel fibres. The addition of steel fibres significantly increased the load-carrying capacity and enhanced the ductility of the post-peak branch. Gribniak et al. [7] experimentally investigated the behaviour of steel fibres-reinforced concrete (SFRC) beams externally bonded with carbon fibres (CFRP) sheets under four points bending test. 20% increase of the ultimate

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https://doi.org/10.1016/j.engstruct.2018.09.052
Received 31 July 2018; Received in revised form 17 September 2018; Accepted 18 September 2018

deformation was observed from the CFRP-strengthened SFRC beams. Debonding of CFRP was also the premature failure and the failure process became gradual and visually apparent due to the added steel fibres. Li et al. [17] conducted an experimental study on hybrid FRP strengthened FRC beams. CFRP and GFRP sheets were used to improve the average rupture strain energy of the FRC beams. Short steel fibres with 0.9% and polymeric fibres with 0.1% volume fraction were used in the concrete mix. Three types of concrete beams were tested, which were plain concrete beams, polypropylene fibres (PF) reinforced concrete beams and PF/SF (steel fibres) hybrid reinforced concrete beams. The hybrid FRC beams strengthened with hybrid FRPs exhibited higher bending stiffness and the crack propagation can be controlled more effectively. Ibrahim et al. [21] investigated short-steel fibres (1.0% volume fraction) reinforced concrete (SFRC) beams retrofitted with GFRP laminates. The GFRP laminates retrofitted SFRC beams exhibited smaller crack spacing and the maximum increase of the ultimate load was found to be 130% as compared to GFRP laminates retrofitted RC beam. They also found that GFRP strengthened SFRC beams only exhibited FRP debonding induced by flexural cracks and none of the beams experienced delamination. In addition, the retrofitted SFRC beams exhibited higher ductility as compared to the retrofitted RC beams. Yin and Wu [8] conducted experimental and numerical studies on the structural performances of short SFRC beams with externally bonded FRP sheets. Four cases with different volume fractions of short steel fibres (0, 0.25%, 0.5%, and 1.0%) were mixed in the concrete beams. The concrete toughness was greatly improved by mixing short steel fibres. The failure mode of FRP-strengthened SFRC beams changed from the interfacial debonding to FRP rupture with a significant increase in the load bearing capacity. The numerical results found that the increase of the fibres volume led to the improved concrete toughness and the fracture energy.

The flexural capacity and shear capacity of FRP strengthened SFRC structures have been investigated [8,17,21]. The FRP-strengthened SFRC beams have similar shear stress and normal stress distributions to the FRP-strengthened RC beams. Interfacial shear stress reaches the peak value at the end part of FRP and decreases nonlinearly with the increasing distance away from the FRP end. The interfacial shear stress is much higher than the normal stress, which is resulted from stiffness change of the strengthened beam at end part of FRP sheet. In addition, it is found that the shear stress of FRP-strengthened SFRC beams with steel fibres is higher than that of the FRP strengthened RC beams and the effective FRP stress transfer length increases with the rising steel fibres volume fraction [8,17]. It is worth noting that no study has been conducted to investigate the interfacial bond behaviour between FRP and SFRC. Therefore, it is important to investigate the interfacial bond behaviour of FRP-to-SFRC. For SFRC, the most important factors influencing the concrete mechanical properties are volume fraction (V_f) and aspect ratio (l/d) of fibres [23]. The volume fraction of steel fibres significantly influences the workability of concrete. The suitable volume fraction of fibres for concrete mixes ranges from 0.25% to 2.5% in volume fraction. The suitable aspect ratio of fibres for concrete mixes is between 50 and 100 [24]. To better understand the effect of short steel fibres on the bonding behavior between FRP and concrete, an experimental program was conducted by using the single-lap shear testing method, which is a reliable method as reported in the experimental program [25] and FEA program [26]. The digital image correlation (2D-DIC) techniques were used in this study to measure the full-field displacements and strains of the specimens. The bond-slip relationship between FRP and concrete can be experimentally obtained from the FRP strain distributions during the loading process. In addition, a fitting procedure was proposed and verified for obtaining the bond-slip curves. The effects of steel fibres on the interfacial bond strength, peak shear stress and the corresponding slip, effective bond length, and interfacial bond-slip relationship were also examined.

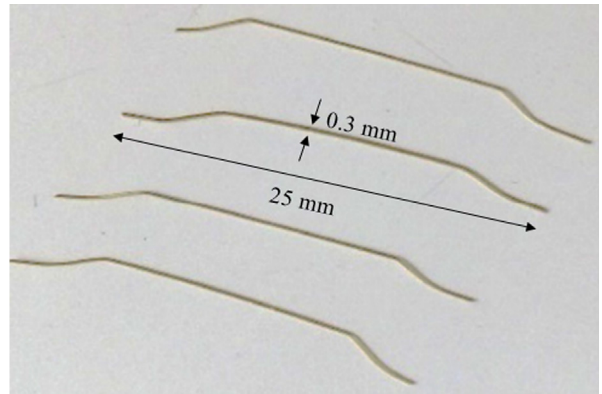

Fig. 1. Short steel fibers.

2. Experimental program

2.1. Material properties

Concrete prisms with a length of 350 mm, width of 150 mm and height of 150 mm were prepared as concrete substrates. Coarse aggregates with size of 5–10 mm was used in the test program. The short steel fibres with the length (L_f) of 25 mm and diameter (ϕ_f) of 0.30 mm (i.e. aspect ratio of 83.33) were used in the testing program, as shown in Fig. 1. Four different volume fractions of short steel fibres, i.e. 0%, 0.25%, 0.5% and 1.0%, were used for the concrete with grade of 40 MPa. The Young's modulus, tensile strength, and density of the short steel fibres are 200 GPa, 2.5 GPa, and 7800 kg/m^3, respectively.

The mechanical properties of PC and SFRC, including compressive strength and splitting tensile strength, were measured to investigate the correlations between the concrete material properties and the interfacial bond behavior. Three concrete cylinders with 100 × 200 mm from each batch of PC and SFRC were tested to obtain the axial compressive strength according to ASTM [27] and other three larger concrete cylinders of 150 × 300 mm dimension were tested based on ASTM [28] for the splitting tension tests after 28 days of curing. The obtained concrete material properties are summarized in Table 1.

Table 1 presents the details of the 12 tested specimens. The specimen ID was assigned to each specimen as "GX_PC/SFRCY_n_m". "GX" refers to the group from G1 to G4, and there are four groups in this study; "PC/SFRC" refers to the type of concrete, i.e. plain concrete (PC) and steel fibres reinforced concrete (SFRC); the letter "*n*" refers to the

Table 1
Mechanical properties of concrete.

Group ID	Specimen ID	Volume fraction V_f (%)	Fiber-reinforcing index *RI* (V_fL_f/ϕ_f)	Compressive strength f_c' (MPa)	Splitting tensile strength f_t (MPa)
G1	PC_1	0	0	40.09	3.98
	PC_2			39.87	4.05
	PC_3			41.05	3.89
	Mean			40.34	3.97
G2	SFRC_0.25_1	0.25	0.208	41.83	4.44
	SFRC_0.25_2			41.05	4.29
	SFRC_0.25_3			40.90	4.16
	Mean			41.26	4.30
G3	SFRC_0.5_1	0.50	0.417	42.59	5.53
	SFRC_0.5_2			44.07	5.28
	SFRC_0.5_3			43.56	5.01
	Mean			43.41	5.27
G4	SFRC_1.0_1	1.00	0.833	43.82	5.93
	SFRC_1.0_2			44.24	5.96
	SFRC_1.0_3			41.32	5.87
	Mean			43.13	5.92