Engineering Structures 143 (2017) 141–151

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental investigation on shear strength of engineered cementitious composites

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ARTICLE INFO

Article history:
Received 9 November 2016
Revised 12 March 2017
Accepted 10 April 2017

Keywords:
Push-off test
Engineered cementitious composites
Ultimate shear strength
Residual stress
Dilatancy

ABSTRACT

This paper describes an experimental study on the shear strength of engineered cementitious composites (ECC). In the experimental programme, twelve push-off tests were carried out on conventional concrete, mortar and ECC specimens. Besides the compressive strength and ductility of materials, the effects of stirrups and dimensions of shear plane were also investigated. Experimental results showed that ECC specimens could sustain significantly greater shear forces than conventional concrete, mainly due to the presence of fibres in the matrix. Instead of severe crushing and spalling in conventional concrete, a major shear crack was observed near the shear plane of ECC specimens, leading to a sudden drop of the shear force. However, when stirrups crossing the shear plane were provided, a certain level of residual forces could be carried by specimens with increasing slip across the shear plane. Comparisons were made between experimental results and design values calculated according to ACI code.

1. Introduction

As a high-performance fibre-reinforced concrete, engineered cementitious composites (ECC) can develop superior strain-hardening behaviour and ultra-high strain capacity in uniaxial tension [1]. Besides, ECC can sustain tensile stresses compatibly with steel reinforcement before its tensile strain capacity is achieved [2]. Thus, when subject to tension forces, the strength of reinforced ECC members can be substantially enhanced through the tensile strength of ECC [3]. The strain-hardening behaviour of ECC can also be taken into consideration in the design of reinforced ECC members under bending moments [4].

Extensive experimental tests have been conducted to investigate the behaviour of reinforced ECC members under various loading conditions [5–7]. Reinforced ECC beams exhibited greater shear resistances than reinforced concrete beams under static loading conditions [8–10]. When subject to cyclic load reversals, reinforced ECC members showed better damage tolerance and energy dissipation capacity [11,12]. Shear failure of beam-column joints could be prevented by using ECC and stirrups in the joints could even be eliminated under cyclic loading [13–16]. Hence, ECC can be utilised in shear-critical members and beam-column joints. However, the behaviour of beams in shear is affected by the shear span-depth ratio and longitudinal reinforcement. Out of conservation, the shear resistance of ECC is simply taken the same as that of conventional concrete in the design guideline published by Japanese Society of Civil Engineers [4].

To quantify the shear strength of ECC, Li et al. conducted experimental tests on ECC beams under shear [17]. Test results showed superior shear strength and strain capacity in comparison with conventional concrete and fibre-reinforced concrete. However, the shear stress distribution was non-uniform across the shear plane. To eliminate the influence of shear stress distribution on shear strength, van Zijl tested ECC beams with a V-shaped notch in which the shear stress was nearly uniform by adjusting the geometry of the notch [18]. Besides, Kanakubo et al. conducted experimental tests on ECC members under combined shear and tension [19]. Nonetheless, the contribution of stirrups to the shear strength of ECC was not considered in these tests, and thus the results could be rather conservative when used for the design of reinforced ECC members in shear.

Push-off tests could be utilised to study the shear transfer of reinforced concrete specimens [20]. Through the tests, the effects of the characteristics of shear plane, stirrups, concrete strength and direct stresses transverse to the shear plane were investigated [21,22]. Later, bending moment across the shear plane was considered in determining the shear transfer strength [23]. In accordance

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http://dx.doi.org/10.1016/j.engstruct.2017.04.019
0141-0296/

with test results, design recommendations are also incorporated in ACI code [24]. The design provisions were further extended to high-strength concrete [25,26]. However, research gaps exist on the shear transfer strength of reinforced ECC specimens under push-off loads.

This paper addresses an experimental study on the shear strength of ECC. In total twelve specimens were tested under push-off loads, in which the effects of compressive strength, strain capacity and ratio of stirrups were considered. Experimental results suggested that compared to conventional concrete, the shear strength of ECC was substantially greater due to its substantially improved strain capacity. Strains of stirrups crossing the shear plane and dilatancy of specimens were measured to shed light on the difference between ECC and concrete. Besides, comparisons were made between test data and code provisions and conclusions were drawn on the design of ECC in shear.

2. Experimental programme

2.1. Mix proportions

Four types of materials, namely conventional concrete, ECC-GGBS, mortar and ECC-FA, were used in the specimens. In the notations, ECC-GGBS and ECC-FA denote ECC with ground granulated blast-furnace slag (GGBS) and fly ash (FA), respectively. Table 1 shows the mix proportions of concrete, ECC-GGBS, mortar and ECC-FA. Conventional concrete was mixed with coarse aggregates of 10 mm maximum size, river sand and cement. In ECC-GGBS and ECC-FA, coarse aggregates were eliminated and silica sand with an average particle size of 0.11 mm was used in place of river sand. The binder in ECC-GGBS contained 70% of GGBS and 30% of ordinary Portland cement. In ECC-FA, the percentages of FA and cement were 65% and 35%, respectively. The materials were such designed that the best ductility of ECC could be obtained under four-point bending. Polyvinyl alcohol (PVA) fibres with a diameter of 0.39 mm and a length of 12 mm were used in ECC-GGBS and ECC-FA. The nominal strength and modulus of elasticity of PVA fibres are 1620 MPa and 42.8 GPa, respectively. In ECC-GGBS and ECC-FA, the volume fraction of fibres was 2%. As for mortar, it contained the same mix design as ECC-GGBS in all respects except PVA fibres.

Fig. 1 shows the parameters in the experimental programme. As the contribution of concrete to shear strength is mainly provided by aggregate interlock after cracking [24,27], ECC-GGBS without coarse aggregates might develop different shear behaviour from conventional concrete under push-off loads. With the same mix proportions except fibres, ECC-GGBS and mortar were expected to reach approximately the same compressive strength. However, the ductility of ECC-GGBS in tension was significantly improved compared to mortar. Thus, the effect of ductility on the shear strength was determined through comparisons between ECC-GGBS and mortar specimens. Even though ECC-FA could demonstrate strain-hardening behaviour, its strain capacity in tension was much higher than that of ECC-GGBS as a result of relatively low compressive strength. Correspondingly, the effect of tensile strain capacity on shear strength could also be studied through comparisons with conventional concrete of nearly identical compressive strengths.

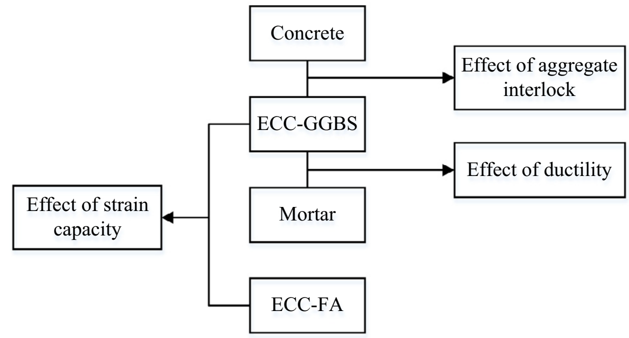

Fig. 1. Parameters in the experimental programme.

2.2. Test specimens

Twelve specimens were tested under push-off loads in the experimental programme. Fig. 2 shows the geometry and reinforcement details of the specimens. The dimensions of shear plane were 250 mm and 125 mm, respectively, and the thickness of the specimens remained constant at 125 mm. In each specimen, ten deformed bars with 16 mm diameter were used for longitudinal reinforcement away from the shear plane to prevent unexpected flexural failure, whereas the number of double-leg stirrups of 8 mm diameter perpendicular to the shear plane varied from zero to four, as summarised in Table 2. Conventional concrete, ECC-GGBS, mortar and ECC-FA were mixed for specimens. In the designations, "NC", "EG", "MT" and "EF" denote specimens made of conventional concrete, ECC-GGBS, mortar and ECC-FA, respectively; "S" represents the shortened shear plane; and the last numeral denotes the number of double-leg stirrups crossing the shear plane.

2.3. Test setup and instrumentation

The specimens were tested by using a universal testing machine. Prior to testing, the specimens were placed on the bottom support of the machine. A compression force was applied to the top of each specimen through a steel plate of 10 mm thickness and 80 mm width, as shown in Fig. 3. Vertical and horizontal deformations were measured during testing. Fig. 3 shows the layout of linear variable differential transducers (LVDTs) mounted on specimens and strain gauges on stirrups crossing the shear plane. To measure the transverse dilatancy of specimens induced by shear force, two pairs of LVDTs (LT-1 to LT-4) were attached on the side faces of specimens with 250 mm long shear plane. However, for EG-S-0 and EG-S-2, only one pair was used at the mid-height of the specimens due to the reduced length of shear plane. Besides, strains of all stirrups were measured by strain gauges at the shear plane. During testing, a concentric load was applied to the specimens and the shear force acting along the shear plane was equal to the applied load. Meanwhile, the slip across the shear plane was also recorded through two vertical LVDTs (LV-1 and LV-2)

Table 1
Mix proportions of materials.

Ingredient	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	GGBS (kg/m^3)	FA (kg/m^3)	PVA fibre (kg/m^3)
Concrete	461	175	512	1252	–	–	–
ECC-GGBS	430	387	287	–	1004	–	26
Mortar	430	387	287	–	1004	–	–
ECC-FA	391	360	504	–	–	727	26