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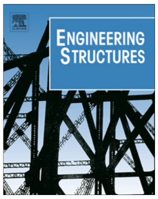

Influence of reinforcement ratio on tension stiffening of reinforced engineered cementitious composites

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ABSTRACT

This paper presents an experimental study on the tension stiffening behaviour of reinforced engineered cementitious composites (ECC). In the experimental programme, ten specimens with concentrically placed steel reinforcement were tested under uniaxial tension. The effects of cross section and longitudinal reinforcement ratio on tension stiffening were investigated. Comparisons were made between ECC and concrete in terms of tension resistance and deformation capacity. Experimental results demonstrated that ECC significantly increased the tension resistance of members at both elastic and post-yield stages of longitudinal reinforcement. Multiple cracks with limited widths and spacings propagated along the length of reinforced ECC at the initial stage. Thereafter, a major crack was formed where the strain capacity of ECC was exhausted, and tension force was transmitted by longitudinal reinforcement across the crack. Localised failure at the major crack eventually led to substantially reduced deformation capacity relative to concrete members. Besides, longitudinal splitting cracks were prevented due to better confinement of ECC. Furthermore, the contribution of ECC to tension resistance was quantified by subtracting the force in longitudinal reinforcement from the total force. Finally, the minimum reinforcement ratio required to ensure adequate force transfer over the major crack was calculated so that full ductility of reinforced ECC members in tension could be achieved.

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1. Introduction

When subject to axial tension, reinforced concrete members develop increased stiffnesses after cracking of concrete compared to bare steel reinforcement, due to participation of concrete between cracks in resisting tensile stresses [1]. At crack planes, reinforcing bars bridge tensile stresses over cracks through bond stresses between the reinforcement and surrounding concrete [2]. Hence, the ability of reinforcement to transmit tensile stresses has to be maintained by providing adequate steel bars. Experimental tests have been conducted on reinforced concrete members under uniaxial tension [3,4]. In addition to transverse cracks, splitting cracks can also be formed along the member length due to insufficient thickness of concrete cover. Splitting cracks have been demonstrated to reduce tension stiffening of reinforced concrete members, as the bond between steel reinforcement and the concrete is reduced and strains of reinforcing bars remain relatively uniform between cracks [5]. However, conventional concrete can only increase the tension resistance of reinforced concrete members when steel reinforcement is at elastic stage. Once the reinforcement yields, the contribution of concrete to tension resistance is neglected.

When fibres are added to concrete, fibres bridging over cracks can sustain significant tension as well as the concrete between cracks [6–8]. As a result, crack widths can be substantially reduced by fibres [9,10], and both elastic and post-yield resistances of tension members can be increased due to the bridging effect of fibres and the improved ductility of concrete [11–13]. As for engineered cementitious composites (ECC), Fischer and Li tested reinforced concrete and ECC specimens in uniaxial tension [14]. Test results showed significant hardening behaviour of ECC in comparison with concrete. So far, most research studies only focus on the enhancement of various types of fibres to the resistance of reinforced concrete members, whereas limited data are available on the influence of fibres on deformation capacity [15]. Moreno et al. conducted a series of uniaxial tension tests to investigate the tension stiffening behaviour of reinforced ECC [16,17]. Test results demonstrated that

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among conventional concrete, fibre-reinforced concrete and ECC, reinforced ECC developed the most significant tension stiffening and premature fracture of reinforcement. Thus, by using ECC in tension members, the deformation capacity was substantially reduced. Although the effect of reinforcement ratio on the deformation capacity of reinforced ECC flexural members has been studied experimentally [18], tension tests on reinforced ECC are still necessary to evaluate the influence of cross section of members and ratio of steel reinforcement on tension stiffening.

This paper describes the influence of reinforcement ratio on tension stiffening of reinforced ECC members. A total of ten specimens were tested under uniaxial tension, of which the influential parameters included material ductility, cross section and longitudinal reinforcement ratio. Experimental results showed that reinforced ECC could develop more significant tension stiffening and deformation capacities of ECC members were greatly reduced compared to conventional reinforced concrete. Besides, splitting cracks along the member length were averted due to better confinement of ECC. In accordance with experimental results, tensile stresses in ECC were calculated and the required minimum reinforcement ratio to develop full ductility of reinforced ECC was determined.

2. Experimental programme on tension stiffening

2.1. Material properties

In the experimental programme, ECC and conventional concrete were used for specimens under uniaxial tension. Table 1 shows the mix design of ECC and concrete. ECC was mixed with cement, water, ground granulated blast-furnace slag (GGBS), silica sand and polyvinyl alcohol (PVA) fibres. The average particle size of silica sand was around 0.11 mm. To achieve desired strain-hardening behaviour, the length of PVA fibres with 0.039 mm diameter was determined as 12 mm and the volume fraction of fibres in ECC was 2%. As for concrete, coarse aggregates with a maximum size of 10 mm were used, as shown in Table 1. Three cylinders of 150 mm in diameter by 300 mm in length were tested for ECC and concrete to obtain the compressive strength. The average values of ECC and concrete were 51.7 MPa and 42.4 MPa, respectively.

To demonstrate the hardening behaviour of ECC, four-point bending tests were conducted on ECC plates of dimensions 75 mm wide by 300 mm long by 14 mm thick. The clear span between vertical supports was 240 mm, with two concentrated point loads applied to one-third of the span. Fig. 1(a) shows a typical load-deflection curve of ECC plates under four-point bending. A linear load-deflection curve was obtained before the cracking load of 300 N. Significant hardening behaviour developed subsequently along with multiple cracks of limited widths (see Fig. 1(b)), and the maximum load sustained by the plate was 384 N. The vertical deflection corresponding to the ultimate load amounted to 17.0 mm.

Deformed bars with diameters of 13 mm, 16 mm and 20 mm were used for longitudinal reinforcement. Tension tests were conducted on steel reinforcement with a gauge length of 300 mm. Stress-strain curves of reinforcing bars were obtained in the tests, as shown in Fig. 2. Table 2 summarises the tensile properties of steel reinforcement. It should be noted that the ultimate strain refers to the strain of steel reinforcement at fracture.

2.2. Specimen design

In total ten specimens were designed and tested under uniaxial tension. Table 3 summarises the details of reinforced ECC and concrete members. In the designations, “NC” denotes conventional concrete; 90, 120 and 150 represent the cross sections of members; 13, 16 and 20 are the diameters of longitudinal reinforcement; and the last numerals represent the reinforcement ratio. The length of specimens remained constant at 1 m, but different cross sections and diameters of longitudinal reinforcement were used in the members. Thus, associated thicknesses of cover and reinforcement ratios varied from each other. The minimum cover of ECC and concrete was around three times the rebar diameter. The ratio of longitudinal reinforcement ranged from 0.59% to 1.64%.

Fig. 3 shows the dimensions and reinforcement detail of ECC-150-13/0.59. A T13 steel reinforcement was placed in the centroid of the specimen. To facilitate the installation of strain gauges, the reinforcement was grooved on both sides over a length of 800 mm along its longitudinal ribs, as shown in Fig. 3. The width and depth of the groove were 4.5 mm and 2.5 mm, respectively. The longitudinal bar was threaded at both ends so that test rigs could be connected to the specimen. As for other specimens, the dimensions of the groove were kept identical, even though rebar diameters were different. At the ends of each specimen, four T10 deformed reinforcing bars were welded to the end plate through full penetration butt weld so that tension force could be directly applied to the specimen.

Fig. 4 shows the test setup for reinforced ECC and concrete specimens. T-shaped steel brackets were connected to the longitudinal reinforcement through bolts and they were clamped by a testing machine to apply tension forces to the specimens. To prevent fracture of steel reinforcement at threaded sections, the brackets were also welded to the end plates of specimens. Strain gauges at 50 mm interval were mounted in the groove of reinforcing bars to measure the strain profile at various loading stages, as shown in Fig. 3. Additionally, two line transducers were fixed on both sides of each specimen and elongation of the specimen over a length of 800 mm was measured.

3. Test results under axial tension

In the experimental tests, applied load and associated elongation of specimens were measured by means of a load cell and line transducers. Tension resistances and deformation capacities were determined from test results. Average strain is calculated by dividing the measured elongation by the gauge length of 800 mm so that comparisons can be made among reinforced ECC, concrete and bare steel reinforcement.

3.1. Tension stiffening effect

Fig. 5 shows the tension force-average strain relationship of reinforced concrete and ECC members at the initial stage. Prior to cracking of concrete, steel reinforcement sustained tensile stresses along with concrete and tension force was almost linearly proportional to average strain in a gauge length of 800 mm. Formation of cracks in the concrete led to several drops of the tension force, as the concrete lost its tensile strength. With increasing strain of

Table 1
Mix design of ECC and concrete.

Material	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	GGBS (kg/m^3)	Sand (kg/m^3)	Fibre (kg/m^3)
ECC	430	387	–	1004	287	26
Concrete	460	175	1077	–	718	–

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