Tensile Strain Hardening Behavior of Cementitious Composites Reinforced with Short Steel Fibres

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Abstract

Short steel fibers have long been incorporated to cement-based materials to improve their low tensile strength and low energy consumption capability, which leads to the steel fiber reinforced cementitious composites (SFRC). However, the conventional fiber volume fraction (V_f) of 1-2% cannot increase the tensile strength of the composites significantly. This has driven investigators towards the development of high performance SFRC using higher fiber volume fractions. The paper reports our experimental investigations of the uniaxial tensile behavior of SFRCs with V_f varying from 2-8%. The preliminary results indicate that strain hardening response can be achieved for the composites reinforced with various steel fibers when the V_f reaches a threshold value. However, their overall performance varies, mainly depending on the properties of the fibers and the fiber volume fractions.

1. Introduction

It is well known that the toughness and the tensile properties of cementitious composites can be improved by incorporating certain amount of short fibers. The mechanical properties of fiber reinforced cementitious composites depend on the properties of the fiber and the matrix, the characteristics of the interface, and the methods of processing.

Conventionally, for cementitious composites reinforced with short steel fibers, the fiber volume fraction in the composites were less than 2%. At such low fiber volume fractions, the improvement on the tensile strength of the composite was insignificant. Moreover, the composites would demonstrate a tensile response of the strain softening type, which is characterized by the widening of a single crack. Fiber pullout dominates the fracture behavior during the process of strain softening. Multiple cracking will normally not occur and strain localization will present instead. The improvements on other properties such as the first cracking strength and tensile strain capacity are also insignificant.

With the advances of fiber reinforced cementitious composites technology, strain hardening and multiple cracking behavior was achieved when aligned continuous fibers were used in the composites [1-3]. Such phenomenon can also be observed by incorporating higher volume fraction of short fibers (say, 8%) in the composites [4-6]. Theories of this kind of behavior were also proposed [7,8]. In these cases, the fibers can, during loading, provide sufficient bridging forces to suppress crack opening and redistribute the stresses to nearby matrix, thus suppressing strain localization and creating multiple cracking. Consequently, the stress and strain capacity of the composite are increased substantially. However, it should be noted that in these pioneer

studies, the matrices of the composites are either cement pastes or cementitious slurries. No coarse aggregate is incorporated, which is not the case of common practical manipulation.

In this study, a series of direct uniaxial tension tests were conducted using adaptive control test method [9,10] on an MTS machine to evaluate the tensile properties of concrete reinforced with short steel fibers. Three kinds of steel fibers were used in the mixtures with fiber volume fraction varying from 2 to 8%. They are Harex, Dramix I and Dramix II fiber. The water-cement ratio was kept constant at 0.45. Water reducing agent and silica fume were used in order to improve the workability of the mixtures and to enhance the bond between the fiber and the matrix. Normal concretes with careful mix proportion design were used as matrices. Plain concrete specimens were also prepared and tested for the purpose of comparison. It was found from this preliminary investigation that strain hardening responses can be achieved for the composites reinforced with these three kinds of steel fibers when parameters were carefully selected.

2. Experimental Details

2.1 Test Program

The objective of the experimental study was to study the overall tension behaviors of concretes reinforced with short steel fibers. The test program is shown in Table 1. The properties of the three kinds of steel fibers are listed in Table 2.

Table 1 Test program

Test Group	Fiber Name	V_f (%)
A	Nil	Nil
B	Harex	2, 3, 6, 8
C	Dramix I	2, 3, 6, 7.5
D	Dramix II	3, 3.5

Table 2 Properties of the steel fibers

Fiber Name	Cross Section	ℓ/d (mm/mm)	Tensile Strength
Harex	arc	32/0.8	0.81GPa
Dramix I	circular	30/0.5	1.2GPa
Dramix II	circular	50/0.5	1.2GPa

2.2 Materials and Mix Proportions

As a control, normal concrete specimens were cast by using type I Portland cement, crushed limestone coarse aggregate of a maximum size of 10 mm with specific gravity of 2.57, natural river sand of a maximum size of 5 mm with fineness modulus of 2.3, and a water-cement ratio of 0.45. To improve the workability, superplasticizer was also used in the mixtures. In SFRC specimens, type U condensed silica fume was also used to enhance the matrix strength and the interface properties between the fiber and the matrix.

Harex steel fiber was manufactured by Harex Metalwork Co. (Shanghai). It has an arc cross section with dimension of 2.2×0.25 mm and length of 32 mm. Dramix I and Dramix II steel fibers were manufactured by N. V. Bekaert Co. (Belgium). They both have hooked ends and a diameter of 0.5 mm, but lengths of 30 mm and 50 mm, respectively. The latter two fibers are the most widely used steel fibers in the market.

The mix proportions for the composites are listed in Table 3.

2.3 Specimen Preparation

All mixtures were mixed in a conventional blade-type concrete mixer. The mixer was first loaded with the coarse and fine aggregate and half of the fibers, then mixed for three minutes. After that, cement and silica fume were loaded and mixed for another three minute. Water and superplasticizer were then added into the mixer followed by adding the rest fibers and mixing

Table 3 Mix proportions

Matrix ^a	Test Group	V_f (%)	C:W:S:A	Admixtures
A ₁	A, B, C	0, 2	1:0.45:1.5:2.5	SP-1% ^b , MS-10% ^c
A ₂	A, B, C	0, 3	1:0.45:2:1.3	SP-1%, MS-10%
A ₃	A, B, C	0, ≥ 6	1:0.45:2:0.65	SP-1%, MS-10%
A ₃	D	3, 3.5	1:0.45:2:0.65	SP-1%, MS-10%

^aSilica fume is not incorporated in plain matrix.

^bSuperplasticizer, in weight of cement.

^cSilica fume, replacement of cement in mass basis.

for five to ten more minutes. There was no problem for fiber dispersion during mixing except for Dramix II steel fiber in which case, the fibers were easy to gather to balls and had to be separated manually. All specimens were cast in a pre-made acrylic glass mold with the specimen dimension of 500×100×20 mm, and were cured in a water tank with a constant temperature of 22°C for four weeks after demolding. After that, they were ground to very smooth surfaces and cut into test dimension of 350×100×20 mm. They were then glued with two aluminum loading plates at both ends and two pairs of steel joint tabs using epoxy (CIBA GEIGY). The joint tab has a descending thickness from 5 mm to 1 mm over a length of 50 mm at the end that contacts with specimen, in order to avoid a sudden change in stiffness and the consequent stress concentration.

2.4 Test Setup and Method

The setup for the test is shown in Fig. 1. Two identical loading fixtures were used. One is gripped on the actuator of the MTS machine, the other is connected to the load cell. The loading fixture contains a ball joint that is essential for preventing the tension specimen from possible bending effects. The glued specimen was connected to the loading fixture by a $\phi 12$ mm pin. Four SCHAEVITZ LVDTs, each with a working range of ± 0.635 mm and gauge length of 120 mm, were mounted on the two sides of the specimen for deformation measurement as well

Fig. 1 Schematic of test setup

as test control. LVDT holders were specially designed to allow for the adjustment of centering and offsetting.

After the specimen together with the LVDTs was mounted onto the testing machine, the LVDTs were manually adjusted to their mechanical zero point, with less than 1% offset allowed. The specimen was then loaded under stroke (ram displacement) control at a rate of 0.01 mm/min. With the increment of tensile load, the slopes of the displacement-time curves of the four LVDTs would exhibit some differences. The test control mode was then switched to dynamic LVDT control among them by choosing the one which shown the largest slope of the output at that time. This so-called adaptive control method was achieved by writing a C program through the interface provided by the MTS Corporation, which allows for unusual test implementation. The displacement rate for LVDT control is 0.003–0.005 mm/min. The normal time for a complete test was around three to four hours. Complete stress-deformation response can always be obtained using this method.

3. Test Results and Discussions

3.1 The LVDTs outputs

The typical deformation-time curves for single cracking case and multiple cracking case are shown in Fig. 2(a) and (b), respectively. It can be found that during testing, the outputs of the four LVDTs differed from each other considerably. In the single cracking case, the loading can be roughly divided into three stages and the control mode for the whole test has to be altered accordingly. At the beginning of the loading (region A in Fig. 2(a)), the specimen behaved elastically and the identical LVDT outputs increased linearly with time. Control mode was set to stroke control at this stage. With the increase of the tensile load, the LVDT readings exhibited some difference (region B in Fig. 2(a)). Control mode had to be altered among the LVDTs according to the slope variations in their deformation-time curves, in order to catch the formation of the matrix transverse crack. From Fig. 2(a), it can be observed that adaptive control is very important to achieve stable post peak response of the specimens because of the dynamic change of the LVDTs' outputs. The subsequent stage (region C in Fig. 2(a)) was dominated by a localized crack and the control mode had to be set to the corresponding LVDT that covered the crack. However, if a wrong control mode is selected, the test will be failed catastrophically.

Fig. 2 Typical deformation-time curves during uniaxial tensile testing

In the multiple cracking case, which will only occur in strain hardening type of response, the outputs of the LVDTs are different from those observed in single cracking case. Fig. 2(b) plots the deformations measured by the four LVDTs as functions of time for the specimen incorporating Dramix II steel fibers with volume fraction of 3.5%. Comparing this figure with Fig. 2(a), it can be found that the outputs of all the LVDTs in Fig. 2(b) develop along their original slope instead of changing over as shown in Fig. 2(a). The change over the slopes in Fig. 2(a) implies that the portions of the specimens covered by corresponding LVDT undergoes a compression instead of tension as a result of single crack opening. On the other hand, the consistent development of deformations along their original direction in Fig. 2(b) implies that strain localization is suppressed and more transverse cracks had been occurred. Optical observation on the specimen demonstrated that the specimen has cracks all over the four regions covered by the four LVDTs. This phenomenon may be attributed to the sufficient bond and bridging force provided by fibers

3.2 Stress–displacement curves

The stress–displacement curves for the matrix concretes and the composites reinforced with the three kinds of steel fibers are shown in Fig. 3(a) through Fig. 3(d), respectively. These results clearly indicate the reinforcing effects of the fibers at different fiber volume fractions. Strain hardening responses can be obtained for these three kind of fibers, although their

Fig. 3 Stress-deformation curves for the matrix concretes and SFRCs

reinforcing effects are different due to the differences in fiber properties. From these figures, it can be observed that

- (a) The behaviors of the three different kinds of matrixes are quite similar under uniaxial tension.
- (b) A higher V_f can result in a better reinforcing effect for the same fiber.
- (c) At a $V_f \geq 6\%$, Dramix I fiber can get a much higher peak load than Harex fiber does. Maximum tensile strength of 12 MPa can be achieved for Dramix I fiber when $V_f = 7.5\%$.
- (d) From strain softening type of response to strain hardening type of response, there exists a transition point of V_f for a definite kind of fiber. Dramix II fiber can achieve strain hardening response even when the V_f is only 3%. Unfortunately however, this fiber is very easy to gather into balls during mixing, which is undesirable for practical use.

4. Conclusions

The preliminary experimental investigation supports the following conclusions:

- (a) The adaptive control is essential to obtain post peak responses for both SFRC and plain concretes under uniaxial tension. During testing, single cracking is essentially different from multiple cracking in both stress–deformation response and outputs of the LVDTs.
- (b) Among the three fibers, Harex and Dramix I fibers can be easily incorporated into the mixtures even when the V_f is as high as 8% due to their relatively lower aspect ratios. But Dramix II fiber is quite difficult to disperse during mixing, even when the V_f is as low as 3%.
- (c) At a $V_f \geq 6\%$, Dramix I fiber can get a much higher peak load than Harex fiber does. Maximum tensile strength of 12 MPa can be achieved for Dramix I fiber when $V_f = 7.5\%$.
- (d) Strain hardening responses can be achieved for the three kinds of steel fibers we investigated, although their overall performance are different due to their different fiber properties and fiber volume fractions.

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