The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

TENSION STIFFENING AND DAMAGE TOLERANCE OF STRAIN-HARDENING CEMENT COMPOSITE (SHCC) TENSION TIES UNDER MONOTONIC AND REPEATED CYCLIC LOADINGS

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ABSTRACT :

This paper describes the influence of cement-based composites' ductility and damage-tolerant capacity on the tension stiffening performance and cracking process of reinforced cement-based composite tension ties. The effect of loading scheme (monotonic and repeated loading) was also investigated. Testing was carried out on six axially loaded tension tie specimens. Each specimen had a square cross-section dimension of 110 x 110mm and length of 500mm. Improved tension stiffening performance in strain-hardening cement-based composites (SHCCs), characterized by the tensile strain-hardening response with multiple cracking, contributes to reduced crack widths, i.e., multiple cracking. Limited amounts of repeated loading with SHCC specimens did not appear to affect the member response nor lead to an increase in crack widths.

KEYWORDS: Strain-hardening cement composite (SHCC), bond stress, ductility, tension stiffening, crack

1. INTRODUCTION

The tensile response of a reinforced concrete (RC) tension ties is shown in Fig. 1. The difference between the bare steel response and actual RC tie response is because even after cracks in the RC tension ties occurred, the concrete still continues to carry tensile load between the cracks through bond between the reinforcing bar and the concrete. This is generally called the tension stiffening effects. Concrete is a relatively brittle material. To improve the tensile response, particularly the ductility of the concrete, the concept of reinforcing concrete with short fibers has been applied. Addition of fibers significantly improves the bond between the matrix and the reinforcing steel and tension stiffening effects by inhibiting crack growth emanating from the bar deformations.

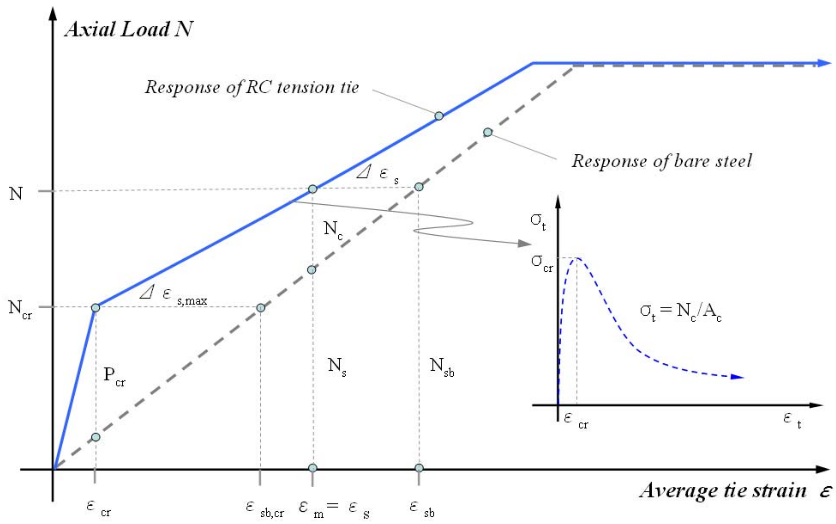


Fig. 1 Typical response of a RC tension tie

In recent years, significant advancements have been made in construction material techniques for improving the performance of brittle cement-based composite. The SHCC or high performance fiber reinforced cement composite (HPFRCC) have been designed with the intent of obtaining a high toughness composite material with strain-hardening and multiple cracking properties. These innovative materials are defined by these particular stress-strain response characteristics in tension, which provide ductile deformation behavior and energy absorption [1], analogous to the elastic-plastic response of metal. Many research results indicate that SHCCs are promising as damage-tolerant materials for seismic applications [2]. For the practical application and design of SHCCs to earthquake resistant structures, it is needed to investigate the interaction characteristics of steel rebars and SHCC. Fischer and Li [3] reported that the engineered cementitious composite (ECC), which is a kind of SHCCs, stiffened reinforced ECC tensile members at uncracked sections and also strengthens them at cracked sections. And they showed the applicability of ECC material for improving the response and ductility of structural members. Mihashi et al [4] investigated bond behavior of deformed bars embedded in HPFRCC reinforced with hybrid fibers, together with steel cord and polyethylene (PE) fibers. It is observed that the bond behavior of reinforcing steel in HPFRCC became very stable and the maximum bond strength increased. Fantilli et al [5] proved the existence of compatible strains between reinforcing steel and HPFRCC by introducing a mechanical model of tension stiffening and referring to tests on reinforced HPFRCC elements in tension.
As pointed out above, interaction between reinforcing steel and cement composite is very different with depending on the kinds of cement composites. Therefore, interaction between reinforcing steel and newly developed SHCC should be investigated urgently to apply SHCC to structural members. This paper investigates the post-cracking response of concentrically reinforced cement-based composite tension ties and compares tension stiffening of plain concrete with SHCCs. The effect of the loading method (monotonic and cyclic loading) is also the principal variable considered.

2. MECHANICAL PROPERTIES OF SHCC

The SHCC matrics used in this particular study utilizes ultra-high molecular weight polyethylene fibers and five twisted steel fibers (i.e., steel cord, or SC), cement, fine aggregates (grain sizes ranging from 105 to 120μm), and methyl cellulous-based viscosity modifying admixture (VMA) 0.2% at cement weight fractions. The SHCCs designated as PE1.50 and PE0.75+SC0.75 are reinforced with 1.5% PE fibers and hybrid 0.75% PE fibers and 0.75% SC. The SHCC matrics' total fiber content is 1.50%. Theses mixes were chosen from among several SHCC mix designs in a preliminary study, and has been proven to have slightly greater tensile strength and tensile strain capacity [6] than the others. The concrete had a specified concrete strength of 50MPa and a 150mm slump. The concrete used coarse aggregates (maximum grain size 15mm), cement, water, and a high-range water-reducing admixture to enhance the fresh properties of the mixture. In order to determine the properties of SHCCs, the following tests were conducted on each of the three cylinders: the monotonic compressive test, repeated compressive test, monotonic tensile test, repeated tensile test, and cyclic tensile and compressive test. The specimens were stored at 23ºC and 95-100% RH for about 24 hours, whereupon they were carefully demolded. Specimens were returned to the same conditions until the day of testing.
Uniaxial compressive and tensile tests were performed on the cylinder specimens to examine the response and fracture process of the damage-tolerant cement-based material, i.e. SHCC in compression and tension. The uniaxial tests were performed by a displacement-controlled testing machine, as shown in Fig. 1. All of the uniaxial tests were performed at a constant engineering strain rate of 0.15% per min. The results are summarized in Table 1. Figure 1 shows a comparison of the typical tensile response of specimens reinforced with a 1.5 percent volume fraction of PE and 0.75 percent of PE and 0.75 percent of SC in fiber volume fraction. PE1.50 composite showed lower peak tensile strength and strain capacity than PE0.75+SC0.75 composite. The typical failure process for two composites at 0.5, 2.0, and 3.0 percent strain on the stress-strain curve are shown in Fig.1.Well-distributed SC macrofibers are more effective at bridging a wide crack formed through the coalescence of microcracks and imparting ductility to the material. The corresponding delay in the development of a critical macrocracks resulted in increased strength and more multiple cracks. The steel reinforcement in all specimen types consisted of one steel reinforcing bar with a 16mm diameter and had yield strength of 392MPa at approximately 0.25% strain.

Table 1 Summary of uniaxial compression and tension results¢

Mixture Proportion	Compression			Tension		
	Strength (MPa)	Maximum Strain¥(%)	Elastic modulus(GPa)	Strength (MPa)	Maximum Strain¥(%)	Elastic modulus(GPa)
Concrete	54.2	0.23	28.2	3.18§	-	-
PE1.50	42.6	0.41	18.7	2.81	0.74	0.16
PE0.75+SC0.75	46.7	0.42	18.9	3.03	1.03	0.18

¢Average results from three specimens, ¥Strain at the maximum strength, §splitting tensile strength

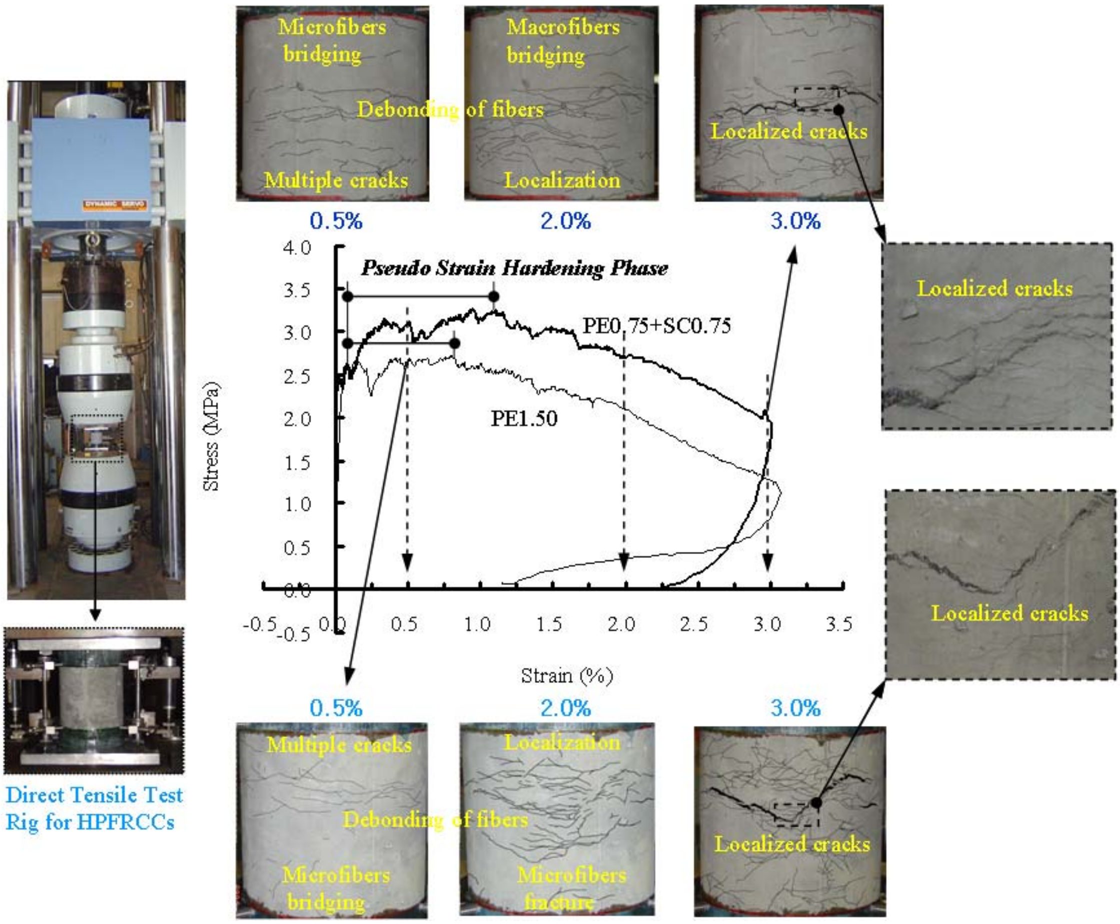


Fig. 1 Typical tensile response and fracture process of SHCCs

3. EXPERIMENTAL PROGRAM

3.1. Specimen configuration

Short term tests of 12 tension ties under axially imposed load were conducted on 55 x 55mm and 110 x 110mm cross sections and 500mm length specimens (Fig. 2) with 16m diameter single bar embedded centrally to give reinforcement ratio of 6.51% and 1.97 %. Five strain gages located on the surface of reinforcing bar were placed adjacent to midspan of the specimen with a spacing of 60mm to monitor the strain of the reinforcement during the deformation process.

3.2. Testing procedure

Tension ties were loaded vertically in a 500kN capacity Universal Testing Machine using tension grips to hold the extended bars at each end (Fig. 3). Average extension was measured over a central 500mm gauge length using two displacement transducer placed on opposite sides of the member and attached to mounting frames firmly clamped onto the specimen. Also two PI gage placed on the notch at the midspan of the specimens with 110 x 110mm cross section to measure the width of crack. The complete response of each specimen is described by plotting the applied tensile stress of reinforcing bar versus strain at the center of specimen.

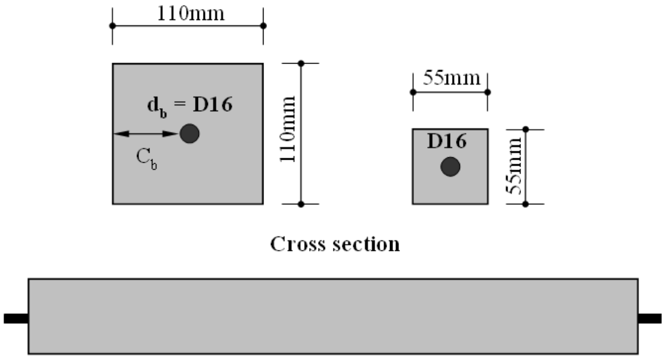


Fig. 2 Configuration and details of tension ties

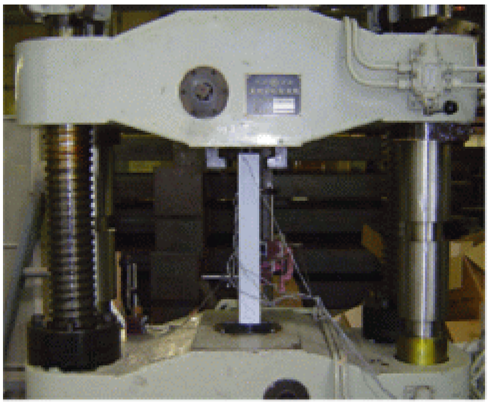
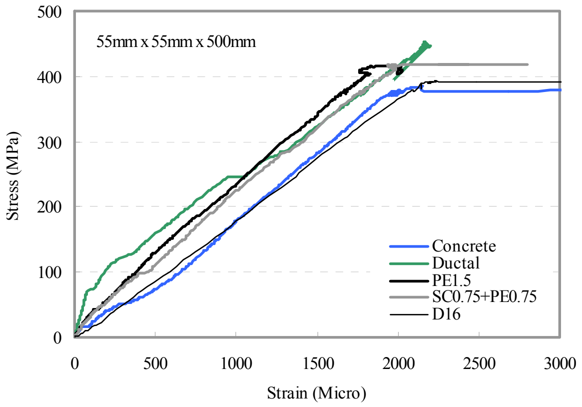


Fig. 3 Test setup of tension ties

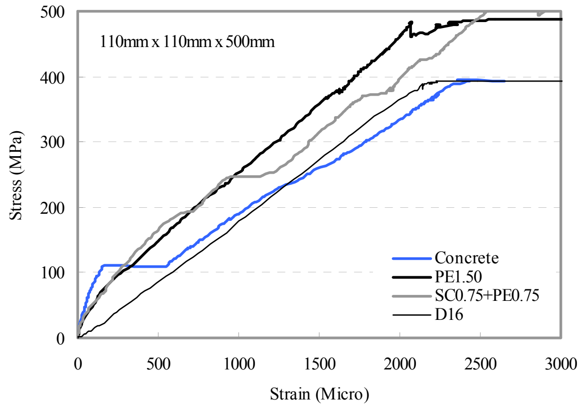
4. EXPERIMENTAL OBSERVATIONS AND RESULTS

4.1. General behavior

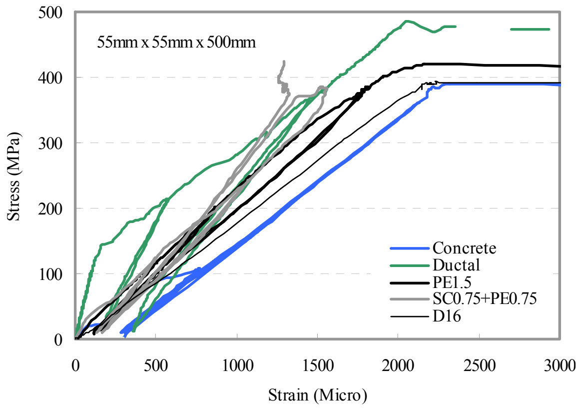
The complete response of each tie is described by plotting the applied tensile stress versus strain of reinforcing bar at the center of the tie. Figs. 4(a) and (b) illustrate the influence of cement matrices and cross section size of



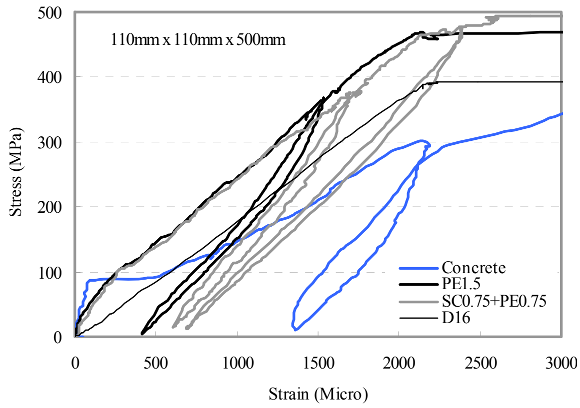
(a) Monotonic responses of small section ties



(b) Monotonic responses of large section ties



(c) Repeated responses of small section ties



(d) Repeated responses of large section ties

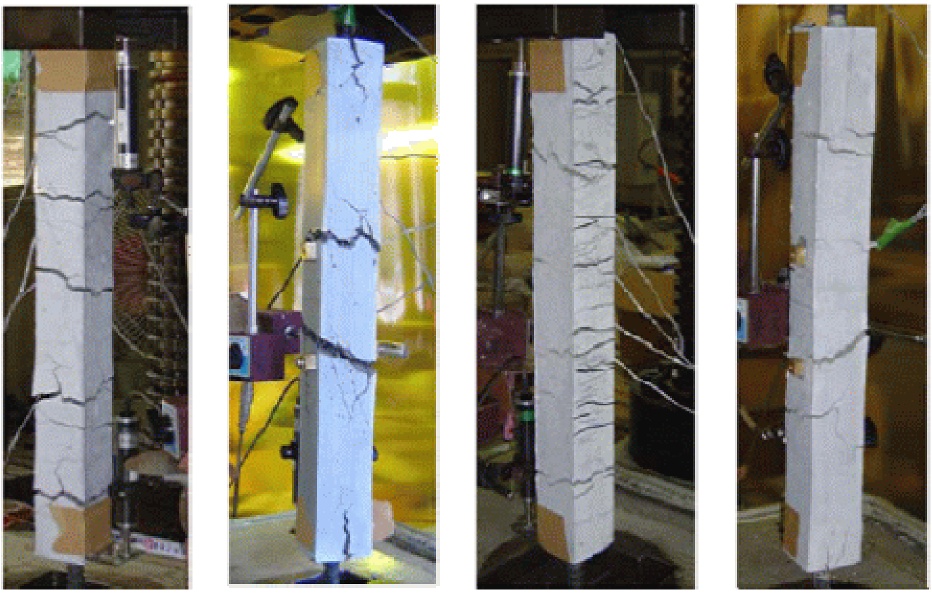
Fig. 4 Steel stress-strain relationships of tension ties

tension ties on the steel stress-strain relationships of four 55 x 55mm small section (c_b = 1.2d_b) and three 110 x 110mm large section (c_b = 2.8d_b) tension ties under monotonic loading, respectively. Also shown in these figures is the response of a bare bar (i.e. without cement-based composite). As can be seen, tensile response of each tie includes elastic uncracked, postcracking, and postyielding regions. The SHCC tension ties exhibit larger postcracking stiffening than the conventional concrete tie. In the initial loading stage of small sections ties, A distinct first cracking point does not appear due to shrinkage-induced cracks formed at the curing of ties. For SHCCs ties with large cross section, it also does not. As shown in Fig. 4(a), commercial SHCC, i.e. Dutal with higher tension strength, stress versus strain response line is both SHCCs above and two SHCCs' responses are parallel. There is not the difference in response between bare bar and concrete tension tie. As can be seen in Fig. 4(b), the presence of 1.5 percent of fibers in cement composite has results in a slight increase in stiffness before cracking and an increase in the cracking load. After cracking, the SHCC with fibers shows more tension stiffening than the conventional concrete without fibers. For conventional concrete, the reinforcing bar must carry all of the tension in the specimen at crack locations. When the applied load cause localized yielding of the bar at a crack then an abrupt loss of stiffness occurs and the response follows that of the yield plateau of the bare bar. A key feature of SHCC is the ability of the fibers to bridge cross cracks. Hence at the locations of cracks in the SHCC, the fibers help the steel bar to carry tension, which can significantly increase the tension stiffening. This also enables SHCC member to carry loads greater than the yield load of the reinforcing bar. Tensile stress versus strain response of reinforcing bar indicates a significant contribution of the SHCC matrix to the tensile strength of the reinforced composite, particularly in the post-yielding regime. For concrete specimens, the reinforcing bar has to carry all of the tension in the specimen at crack locations. When the applied tension load causes localized yielding of the bar at a crack then an abrupt loss of stiffness occurs and the response follows that of the yield plateau of the bare bar [Figs. 4(a) and (b)]. Figs. 4(c) and (d) show results of cyclically loaded specimens. Specimens were repeatedly loaded two times at the strain levels of 1500 and 2000$\mu\varepsilon$. Results suggest that limited amount of repeated loading do not affect tension stiffening of SHCC significantly for the type and dosage of fibers used in this study while the tension stiffening performance of concrete under repeated loading decrease more seriously than that of concrete under monotonic loading. In concrete specimen under repeated loading, abrupt decrease of stiffness is due to bonding loss and separation of surface concrete. The results presented in Fig. 4 also show the influence of the different concrete cover (c_b). Tension stiffening effects are influenced by the concrete cover, i.e. the ratio concrete cover-to-rebar diameter. The tension stiffening contribution, in fact, increases when the concrete cover of rebar increases as well.

4.2 Crack procedure

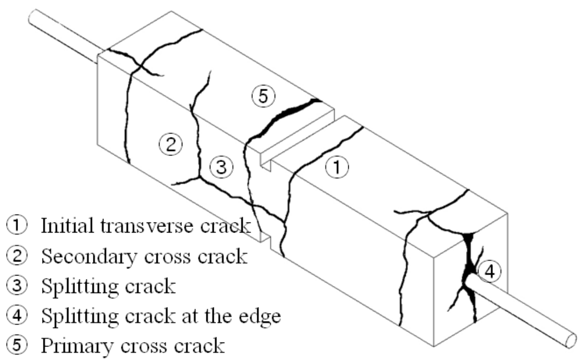
For concrete and Ductal ties, one can first observe the appearance of the initial transverse crack on the center of tie length. In each tie, some cracks (primary transverse cracks) seemed to dominate until they all reached the same crack width, then they stopped and allowed other cracks to widen. This cracking process is more likely to occur in the concrete and Ductal. Longitudinal splitting cracks could be detected at the ends of tie elements. This occurred for large deformations, usually near yielding of the steel reinforcing bar. This may be explained by the Poisson's effect and the ensuing high splitting pressure due to dislodgment of the lugs of the reinforcing bar. Then, under higher load, the same splitting phenomenon reappeared when the concrete and Ductal body was segmented into separate blocks for deformations well beyond yielding of the reinforcing bar shown in Fig. 5. At last, a secondary transverse network of cracks grows from the splitting crack. The cracking pattern evolves until the steel yields. Testing of concrete ties was terminanted due to composite disintergration when large parts od concrete matrix detached from the reinforcement and major spalling occurred.

In the SHCC ties, the first transverse crack does not increase in width as the results of direct tension tests for SHCCs shown in Fig. 1. Many fine cracks contiunously develop along the tie length up to peak load and their width remains below 200 micro-meter. This stage is known as multiple cracking, one of the most improtant and distinctive properties of the HPFRCCs. The cracks were not always simultaneously visible on all four sides of the tie. No longitudinal cracking, except the the ends of ties, or matrix spalling from the reinfrocing bar is observed throughout the test. Localization of cracking in the SHCC matrix was observed near peak load. In the PE1.50 and SC0.75+PE0.75, the transverse cracks were smaller and more closely spaced than conventional concrete and RPC. From Fig 5, the difference material characteristics of concrete, Ductal and SHCCs become apparent at the formation of transverse cracking in the SHCCs.

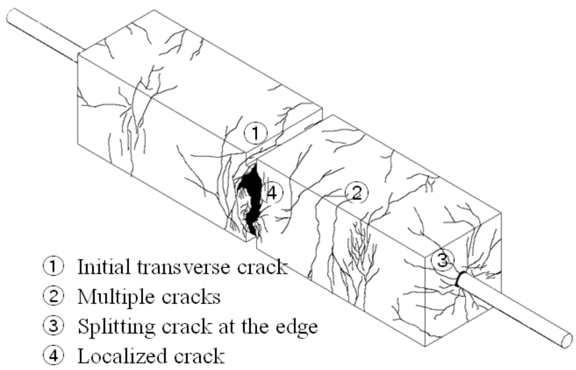


(a) RC (b) Ductal (c) SHCC(PE1.50) (d) SHCC(SC0.75+PE0.75)

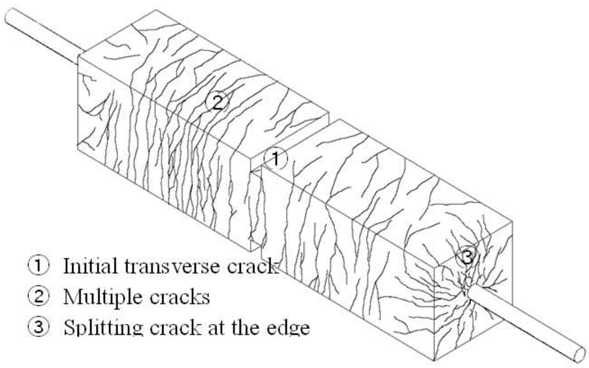
Fig. 5 Typical final failure patterns of ties with small cross section



(a) RC tie



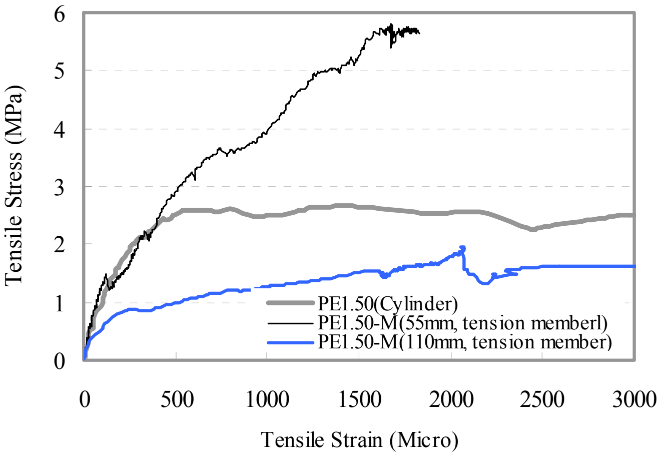
(b) SHCC tie (PE 1.50)



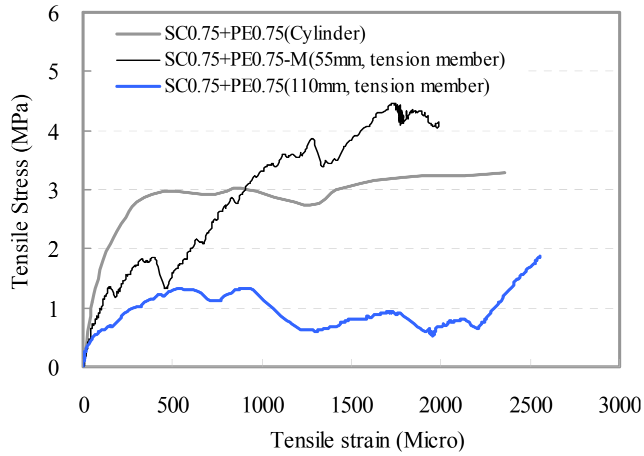
(c) SHCC tie (SC0.75+PE0.75)

(d) Final failure patterns

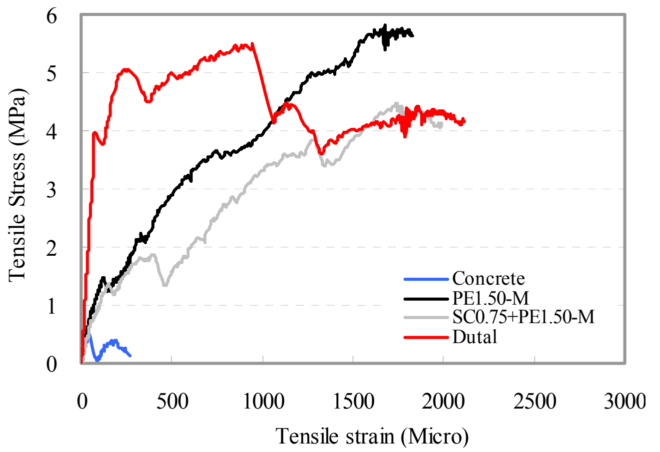
Fig. 6 Typical cracking patterns of ties with large cross section



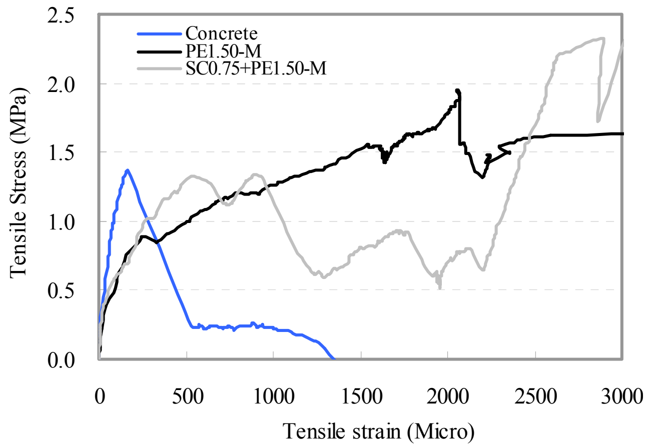
(a) SHCC (PE 1.50)



(b) SHCC (SC0.75+PE0.75)

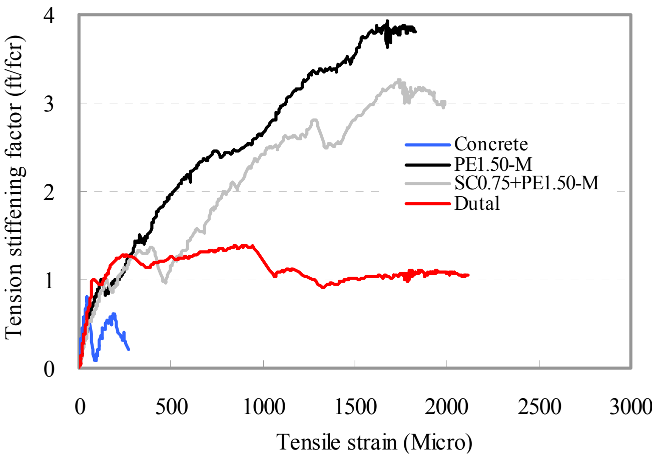


(c) Ties with small cross section

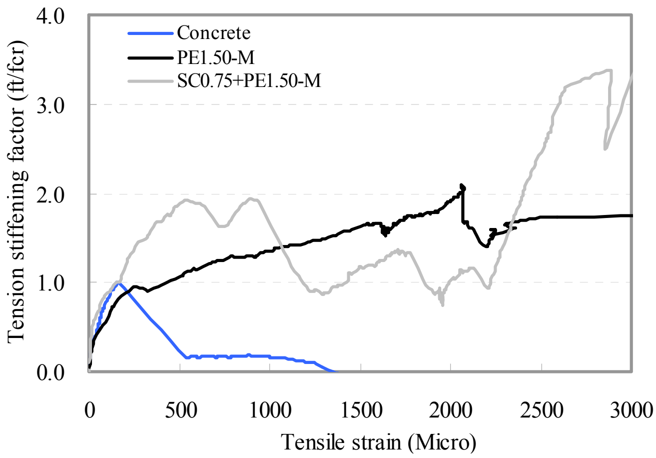


(d) Ties with large cross section

Fig. 7 Tensile stress-strain relationship of cement-based matrix under monotonic loading



(a) Ties with small cross section



(b) Ties with large cross section

Fig. 8 Tension stiffening factor (β) of tension ties

4.3 Tension stiffening response

The tensile force carried by the cement composites is obtained by subtracting the bare bar response from the measured member response. Dividing this force by the effective area of cement composite in tension gives the average tensile stress carried by cracked cement composites. This then results in a tension stiffening factor ($\beta=f_c/f_{cr}$) when normalized with the tensile cracking strength. Tension stiffening factor represents the average stress

(f_c) carried by the cracked cement-based matrix, which is normalized with the cracking stress (f_{cr}). Fig. 7 presents tensile stress carried by SHCC. The damage tolerance of SHCC improves tension stiffening of cement composite. As expected, SHCC specimens exhibited larger amounts of tension stiffening than the companion normal concrete tension tie [shown in Fig. 7(c)]. Fig. 8 shows tension stiffening factor for concrete and two kinds of SHCCs. The tension stiffening factor of concrete in linear up to the cracking strain but, once crack, it decrease fast. Fig. 8 clearly shows that SHCCs exhibit different characteristics compared with normal concrete.

5. CONCLUSIONS

(1) The damage tolerance of fiber-reinforced cement composite result in two times increase in tension stiffening of SHCCs and 23-33% in yielding strength of bar in SHCCs.
(2) Limited amounts of cyclic loading do not affect tension stiffening of SHCC used in this study while tension stiffening performance of regular concrete decrease abruptly after the first cycle. The number of cracks and average width of cracks appear to be unaffected by cyclic loading when compared to the monotonic response.
(3) SHCC tension ties exhibited smaller cracking spacings, and the resulting greater number of cracks leads in parts to an observed reduction in crack widths.

ACKNOWLEDGEMENT

This research has been supported by Korea Government (Brain Korea 21).

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