- Technical Paper -

THE INFLUENCE OF CEMENT COMPOSITE DAMAGE TOLERANCE ON THE TENSION STIFFENING AND CRACKING OF REINFORCED CEMENT COMPOSITE TENSION TIES

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ABSTRACT

The purpose of this research was to investigate the influence of cement composite damage tolerance on the tension stiffening performance and cracking process of high-performance fiber-reinforced cement composites (HPFRCC) 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 HPFRCC contributes to reduced crack widths, i.e., multiple cracking.

Keywords: HPFRCC, bond stress, ductility, tension stiffening, crack

1. INTRODUCTION

Cementitious composite is considered a brittle material, the nearly complete loss of loading capacity once failure is initiated. This characteristic, which limits the application of the material, can be overcome by the inclusion of a small amount of discontinuous fibers uniformly distributed throughout the cementitious material. In recent years, significant advancements have been made in construction material techniques for improving the performance of brittle cementitious composite. The HPFRCCs characterized by the tensile strain-hardening response with multiple cracking, have been developed. The properties of HPFRCCs have been extensively investigated. Research results indicate that HPFRCCs are promising as damage-tolerant materials for seismic applications. Several applications of HPFRCCs to seismic design or retrofit, such as passive infill panel systems, moment frames, beam-column joint regions, energy dissipating dampers, and coupling beams for coupled shear walls, have been studied or are currently under investigation.

Cracking significantly affects the behavior of reinforced concrete structures. Once cracked, reinforcement is assumed to carry all of the tensile force at the cracks; however, concrete continues to carry tensile load between the cracks through bond between the reinforcing bar and the concrete. This is called tension stiffening. The ability of concrete to carry tension between cracks in a reinforced concrete member helps control member stiffness, deformation, and crack widths that are related mostly to satisfying serviceability requirements. Tension stiffening also plays an important role in nonlinear analysis of reinforced concrete (Bischoff [1], 2003). For the practical application and design of HPFRCCs to earthquake resistant structures, it is needed to investigate the interaction character-ristics of steel rebars and HPFRCC. Application of HPFRCCs to structural members is one of key issues for mitigating damage of concrete structures in strong earthquakes. The control of crack widths (distribution) in reinforced concrete structures is also required for long term durability.

This paper investigates the postcracking response of concentrically reinforced cementitious composite tension ties and compares tension stiffening of plain concrete with HPFRCCs. The effect of the loading method (monotonic and cyclic loading) is also the principal variable considered.

2. HPFRCC CHARACTERISTICS

2.1 Compositions

The HPFRCC materials used in this research are comprised of a Portland cementitious matrix

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Table 1 Mixture proportions of composites

Composite	w/c	Fiber volume fraction (%)		Unit weight (kg/m^3)		
		SC	PE	Cement	Sand	Water
Concrete	0.45	-	-	495.0 1,240.0*	637.0 932.0**	198.0
PE1.50		-	1.50	1,046.5	418.6	470.9
SC0.75+PE0.75		0.75	0.75	1,041.0	416.6	468.7

* Weight of fly ash, ** Gravel weight

(the water-to-cement ratio of 0.4) with a low fraction of both polymeric and steel fibers. The cementitious matrix consists of fine silica sand with a specific gravity of 2.61 and grain sizes ranging from 105 to 120μm. Details of the mix design are provided in Table 1. This mix was chosen from among several HPFRCC mix designs in a preliminary study, and proved to have slightly greater tensile strength and tensile strain capacity [2]. To compare to HPFRCC, commercial RPC and regular concrete was used. The pertinent fiber characteristics are shown in Table 2. The polyethylene (PE) fibers are an ultra-high molecular weight polyethylene material. The steel cord (SC) is composed of five thin steel fibers that are twisted together. Since SC has a rough surface, it offers much higher interfacial bond strength than that of straight fibers.

2.2 Characteristics

The material tests in this study were used to get basic information on the comparative material properties of the different composites and plain concrete. Adequate number of specimen was cast in each case to provide information on the ultimate strength and strain capacity in both compression and tension. Cylindrical specimens, 100mm in diameter and 200mm tall, were used for uniaxial compression and tension tests. The uniaxial compressive and tensile tests were performed by a displacement-controlled testing machine shown in Fig. 1. The results are summarized in Table 3. Fig. 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.

3. TEST PROGRAM

3.1 Specimen configuration

Each specimen had two cross-sectional dimensions of 110 mm by 110 mm and a length 500mm. To predetermine the location of the first

Table 2 Properties of hybrid fiber reinforcements

Fiber	Specific weight (kg m^{-3})	Length (mm)	Diameter (μm)	Aspect ratio	Tensile strength (MPa)	Young's modulus (GPa)
Steel cord	7,850	32	405	79	2,300	206
PE(DYN-A)	970	15	12	1,250	2,500	75

Table 3 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 transverse cracking, a notch (a =15mm) was inserted at midspan of the tension tie. Five strain gages located on the surface of reinforcing bar (shown in Fig. 2) were placed adjacent to midspan of the specimen with a spacing of 60mm to monitor the strain of the reinforcement during the deformation process. The reinforcement consisted of one steel reinforcing bar with a 16mm diameter.

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 (Figure 1). 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 specimen 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.

4. TEST RESULT AND DISCUSSION

4.1 Member response

The complete response of each specimen is described by plotting the applied tensile stress of reinforcing bar versus strain at the center of the specimen. Fig. 3(a) shows the reinforcing bar tensile stress versus strain responses of three specimens under monotonic loading. Also shown in this figure is the response of a bare bar (i.e. without cementitious composite). As can be seen, 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 HPFRCC 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

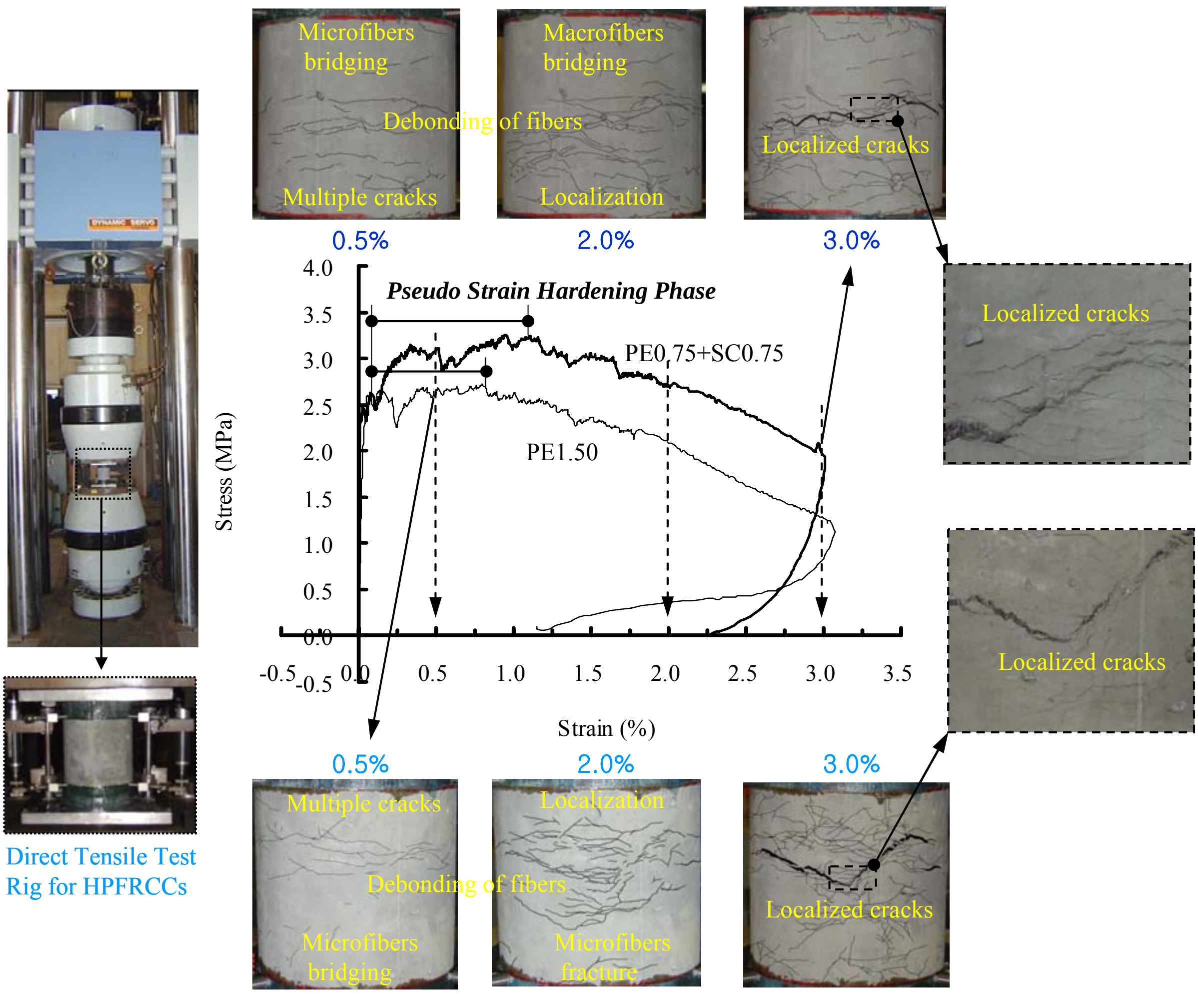


Figure 1 Typical tensile response and fracture process of HPFRCCs

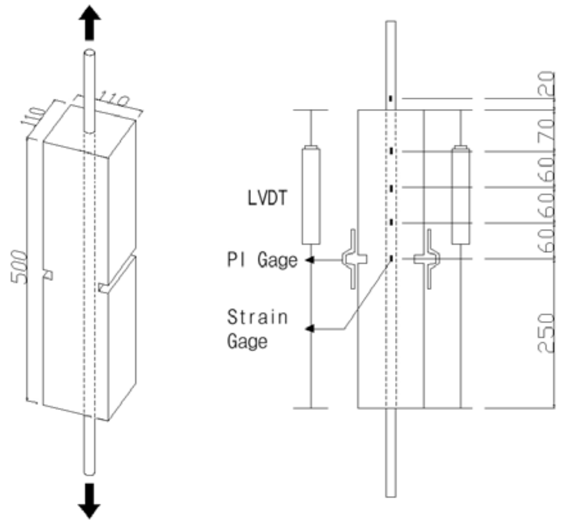
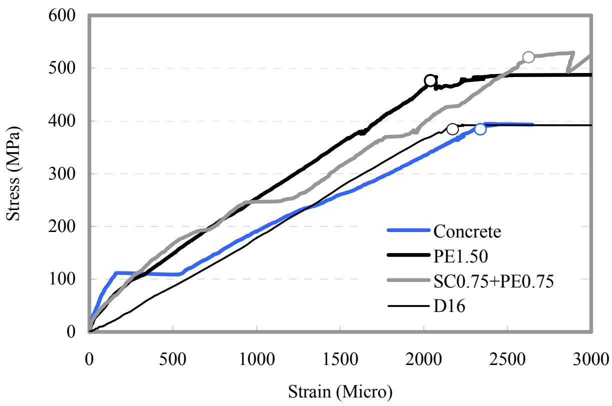
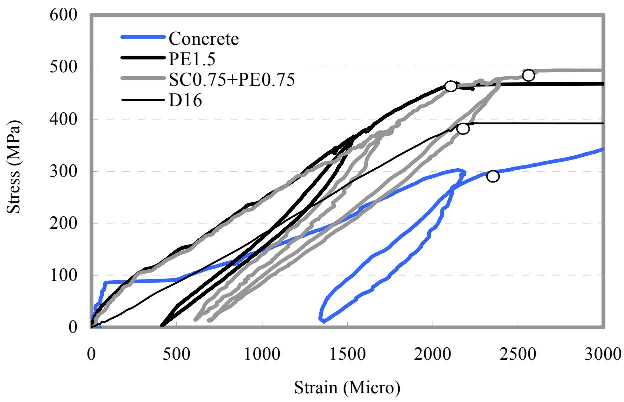


Figure 2 Tension tie details (unit :mm)

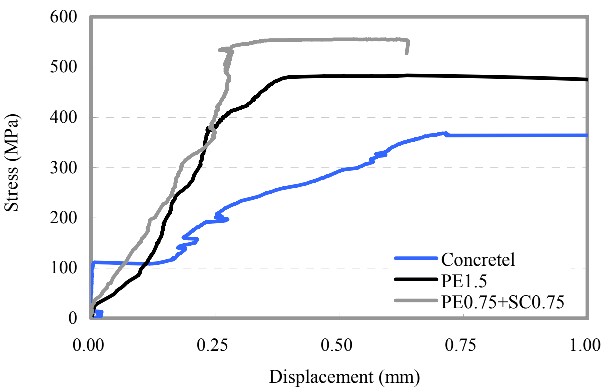
HPFRCC is the ability of the fibers to bridge cross cracks. Hence at the locations of cracks in the HPFRCC, the fibers help the steel bar to carry tension, which can significantly increase the tension stiffening. This also enables HPFRCC member to carry loads greater than the yield load of the reinforcing bar. PE1.50 and SC0.75+PE0.75 lacks a distinct first cracking stress due to shrinkage induced cracks formed prior to testing [Fig. 3(a)]. Tensile stress versus strain response of reinforcing bar indicates a significant contribution of the HPFRCC matrix to the tensile strength of the reinforced composite, particularly in the postyielding 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 [Fig. 3(a)] Fig. 3(b) show results of cyclically loaded specimens. Specimens were repeatedly loaded two times at the strain levels of 1500 and 2000με. Results suggest that limited amount of repeated loading do not affect tension stiffening of HPFRCC 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 circle(○) in Figs. 3(a) and (b) mean the yielding of reinforcing bar embedded in the cement-based composites. Figures 3(c) and (d) show the response between tensile stress and the mouth opening displacement of the crack (notch) at the midspan of tension tie. These responses are similar to those of reinforcing bar.



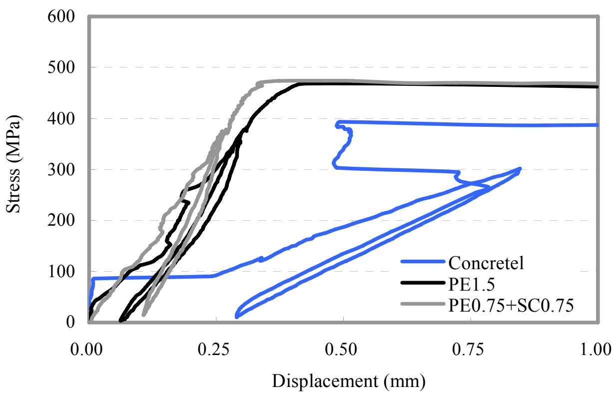
(a) response of bars under monotonic tension



(b) response of bars under repeated tension



(c) notch crack width under monotonic tension



(d) notch crack width under repeated tension

Figure 3 Responses of tension ties

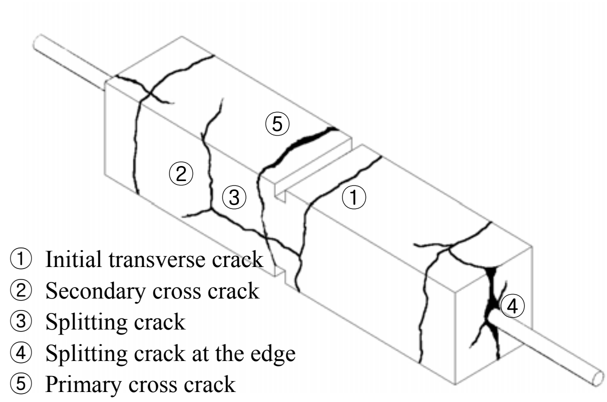
4.2 Crack procedure

Typical crack patterns for three tension specimens constructed with conventional concrete and HPFRCC with PE fiber, with hybrid fiber (SC and PE), are shown in Fig. 4. As can be seen from this figure, both transverse cracks and splitting cracks were observed during the test for conventional concrete. In the PE1.50 and SC0.75+PE0.75, no splitting cracks were observed during the test, and the transverse cracks were smaller and more closely spaced than conventional concrete. 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. The cracking pattern evolves until the steel yields. Testing of concrete ties was terminated due to composite disintegration when large parts of concrete matrix detached from the reinforcement and major spalling occurred.

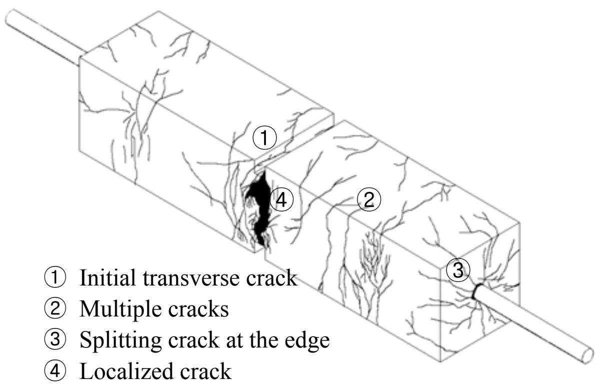
In the HPFRCC ties, the first transverse crack does not increase in width as the results of direct tension tests for HPFRCCs shown in Fig. 1. Many fine cracks contiunously develop along the tie length up to peak load and their width remains below 200 micro-meter. This stage is known as multiple cracking, 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. As shown in Fig. 4(b), localization of cracking in the HPFRCC 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.

4.3 Tension stiffening response

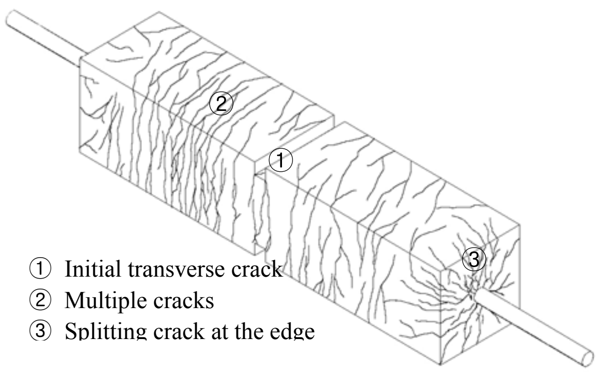
The tensile force carried by the cement composites is obtained by subtracting the bare bar response from the measured member response. Dividing this force by the effective area of cement composite in tension gives the average tensile stress carried by cracked cement composites. This then results in a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



(a) concrete tension tie



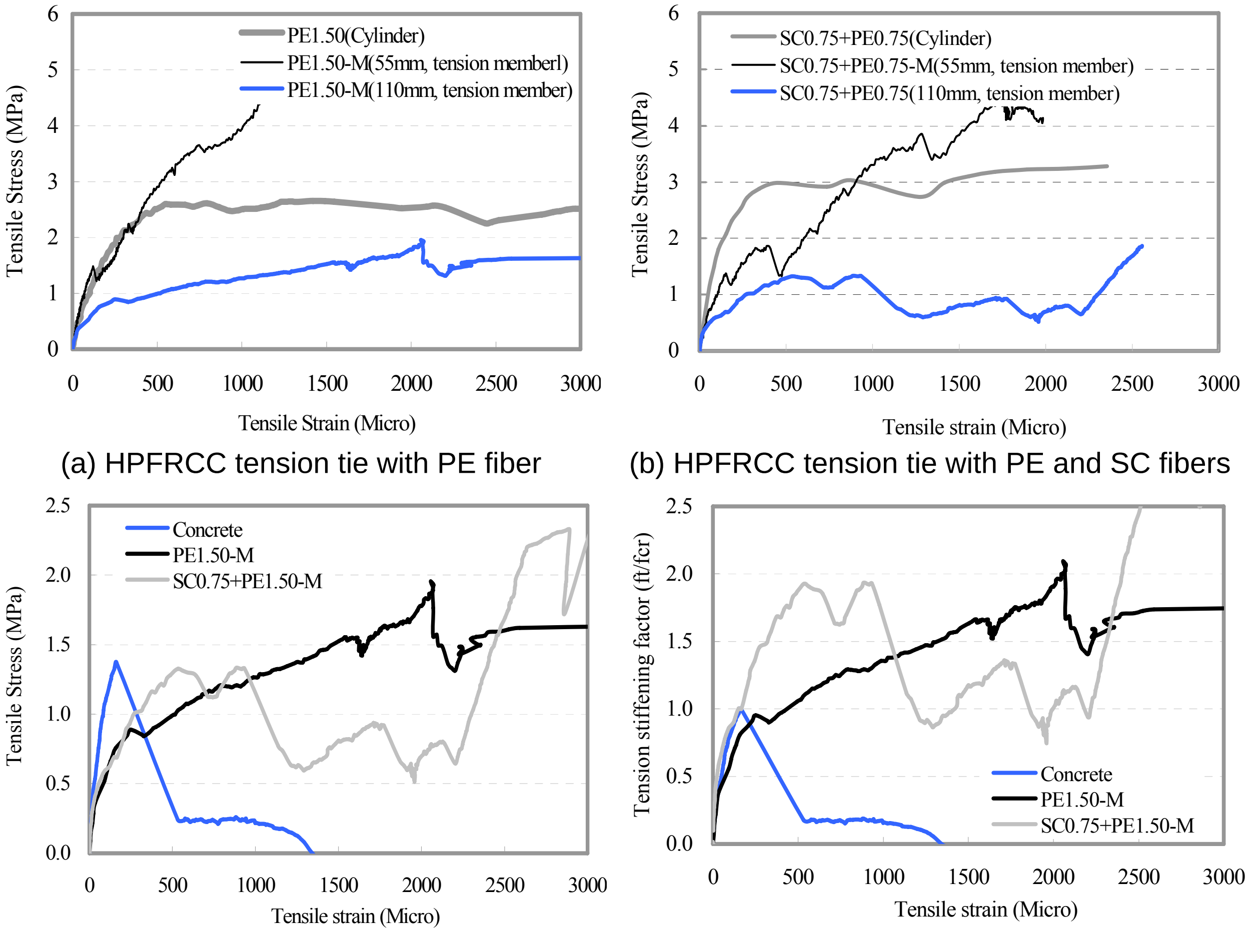
(b) HPFRCC tension tie with PE fiber



(c) HPFRCC tension tie with PE and SC fibers

(d) final crack patterns of tension ties

Figure 4 Cracking procedure and final failure patterns of tension ties



(c) comparison (d) Tension stiffening factor (β)

Figure 5 Tensile stress-strain relationship of cementitious matrix under monotonic loading

stress (f_c) carried by the cracked cementitious matrix, which is normalized with the cracking stress (f_{cr}).

Figs. 5(a) and 5(b) present tensile stress carried by HPFRCC. Previous test results[3] by authors are compared in the figures. The damage tolerance of HPFRCC improves tension stiffening of cement composite. As expected, HPFRCC specimens exhibited larger amounts of tension stiffening than the companion normal concrete tension tie [shown in Fig. 5(c)]. Fig. 5(d) shows tension stiffening factor for concrete and two kinds of HPFRCCs. The tension stiffening factor of concrete in linear up to the cracking strain but, once crack, it decrease fast. Fig. 5(d) clearly shows that HPFRCCs 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 HPFRCCs and 23-33% in yielding strength of bar in HPFRCCs.

(2) HPFRCC tension ties exhibited smaller cracking spacings, and the resulting greater number of cracks leads in parts to an observed reduction in crack widths.

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