BOND BEHAVIOR OF A DEFORMED BAR IN HIGH-PERFORMANCE FIBER-REINFORCED CEMENT COMPOSITES (HPFRCC)

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ABSTRACT

Development of highly ductile concrete members is one of the key issues for mitigating damage of concrete structures in strong earthquakes. Reduction of crack width is also required for durability and long life of concrete structures. For such purposes, a kind of high-performance fiber-reinforced cement composite (HPFRCC) was developed by means of hybrid fiber reinforcement together with steel cord and polyethylene fiber. Bond behavior of deformed bars embedded in such a very ductile composite is studied. It is also demonstrated how the flexural behavior of beams is influenced by changing the matrix.

1 INTRODUCTION

Bond between steel and concrete is one of the key of the resistant mechanisms of reinforced concrete structures and there have been many test results and analyses published in these last thirty years [1]. While the bond mechanism controls the force transfer from steel to concrete, stress in a reinforcing bar changes along its length and the steel strain at a point is different from the strain of the neighboring concrete but a relative displacement between the steel and the concrete occurs. It is called "slip" that is also due to the effect of the highly-localized strains in the concrete layer closest to the reinforcement. The bond behavior of pulled-out reinforcing bars embedded in concrete is characterized by four different stages [1]. The global behavior results from the superposition of the various stages of local behavior of bond. Thus the bond behavior becomes very complex. It is well known that bond behavior depends on various factors but there are quite few previous reports dealing with the influence of crack resistance of the matrix (i.e. concrete) on ductile deformation characteristics. Noghabai [2] studied the structure-material-load interaction, in which the influence of compressive strength of concrete and with or without different types of fibers (V_f = 1%) on bond behavior of deformed bars was investigated. Fisher and Li [3] investigated the influence of mechanical properties of fiber-reinforced composites, particularly strain hardening and multiple cracking, on the tension stiffening effect of steel-reinforced composite elements in uni-axial tension. Because of the very ductile deformation characteristics, the strain incompatibility between steel and matrix drastically reduced. As the result, damage induced by local slip and excessive interfacial bond stress between reinforcement and matrix was prevented. Otsuka and Mihashi [4] published a paper in which detailed process of bond crack formation in HPFRCC around a deformed bar under uni-axial tension was observed by means of X-ray technique with a contrast medium. While the initial crack starts from the notch at the center of the specimen, the width of the primary crack does not extend but a number of other bond cracks are accumulated even after the yield point of the deformed bar.

The purpose of the present paper is to show some results of an experimental study in which the influence of ductile deformation characteristics of the matrix on bond behavior and local strain distribution in the reinforcement are studied. Comparison of flexural behaviors of reinforced beams made with ordinary concrete and HPFRCC are also demonstrated by FEM analysis.

2 EXPERIMENTAL PROGRAM

The materials used in this study are high early Portland cement (C), super plasticizer (SP), silica fume (SF), fine silica sand (S), polyethylene fiber (PE), and steel cord (SC). The steel cord is composed of five very thin steel fibers that are twisted together. Since the steel cord has a rough surface, it offers much higher bond strength than that of straight fibers. Table 1 shows the properties of the used fibers.

Specimen configuration is shown in Fig. 1. Specimens had cross sectional dimensions of 140x70 mm and the length of 500 mm. A single deformed bar of D16 was embedded in the center of the prism made with different types of matrix. Table 2 shows the mix proportions of the matrix. Three kinds of matrix were used, one of which was FRCC reinforced with only polyethylene fiber (F-1.5) and the others were hybrid fiber reinforced cement composites (H-1.5 and H-2.0). In the FRCC, the volume content of the polyethylene fiber was 1.5 vol.%. In the hybrid fiber reinforced cement composites, the volume content of the polyethylene fiber was constant (1.0 vol.%) and the steel cord was 0.5 vol.% (H-1.5) or 1.0 vol.% (H-2.0).

In order to prevent debonding between the reinforcing bar and the matrix, spiral hoop was provided over a length of 100 mm on each end. Strain gages were mounted on the surface of the deformed bar with a spacing of 30 mm or 40 mm to measure the local strain distribution. The overall specimen deformation was also measured by a pair of linear voltage differential transducers (LVDTs) on both sides of the specimen using a steel frame mounted to the both end surfaces as shown in Fig. 1. Specimens were loaded by a servo-hydraulic testing machine and the tensile load was transferred from three reinforcing bars to the specimen at the both ends, though the main part of the specimen (80% of the central part) was reinforced with a single bar. Displacement control system was adopted for the loading.

Table 1 Properties of used fibers

	Density (kg/m^3)	Length (mm)	Diameter (μm)	Aspect ratio	Tensile sterngth (MPa)	Modulus of elasticity (GPa)
Polyethylene fiber	970	6	12	500	2770	88
Steel cord	7840	32	415	77	2650	160

Table 2 Mix proportions of matrix

Series	W/B [wt.%]	SF/C [wt.%]	S/B [wt.%]	Fiber [vol.%]	
				SC	PE
F-1.5	40.0	15.0	40.0	-	1.5
H-1.5				0.5	1.0
H-2.0				1.0	1.0

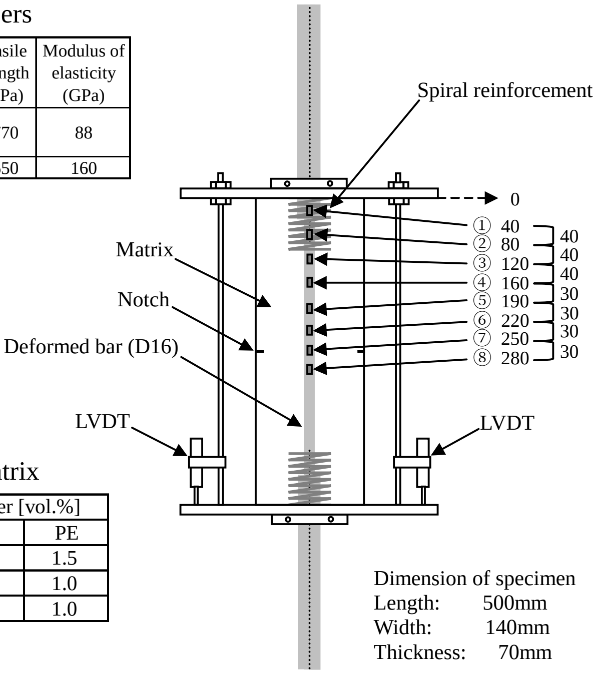


Fig.1. Configuration of specimen

3 EXPERIMENTAL RESULTUS AND DISCUSSION

Typical examples of global behavior of bond (a stress-strain relationship counted for the bar) in each case are shown in Fig. 2. Stress drops observed in the solid lines around the strain of 0.7 % were caused by stress relaxation during the bond crack observation by means of X-ray technique with a contrast medium [4]. The dotted line in Fig. 2 shows the stress-strain relation obtained by a tension test on a bare deformed bar. Because of the composite effect, the initial stiffness is much higher than that of the bare bar. In the ascending portion around 230 MPa, the initial slope changed. This may be related to the crack initiation in the matrix. After this point, the curve approached to the line obtained by the tension test on a bare bar, though the tension stiffening effect is more dominant than that of ordinary concrete shown in previous studies [1]. Moreover it is noticeable that the tensile stress is still increasing even after the yielding point of the bare bar especially in cases of H-1.5 and H-2.0 in which the matrix was made with hybrid fiber reinforced cement composites.

Figure 3 shows the relationships of tensile strain and nominal stress of the matrix which were calculated step by step from the difference between the whole external force and the force shared by the steel bar at a given strain, that is, the total force minus the force measured in the tension test on the bare bar. As the volume content of steel cord increased, the first peak and the maximum stress clearly increased. In all cases, there is a drop of the stress and the stress-strain curve looks like a valley around 0.2 % of the strain. Relaxation from the first peak to the bottom of the valley at the strain 0.2 % was caused probably by crack initiation and propagation in the matrix from the regions close to ribs of the deformed bar [4]. Once the reinforcing bar yields, the stiffness of the reinforcing bar was suddenly lost and the matrix shared again a large part of the stress.

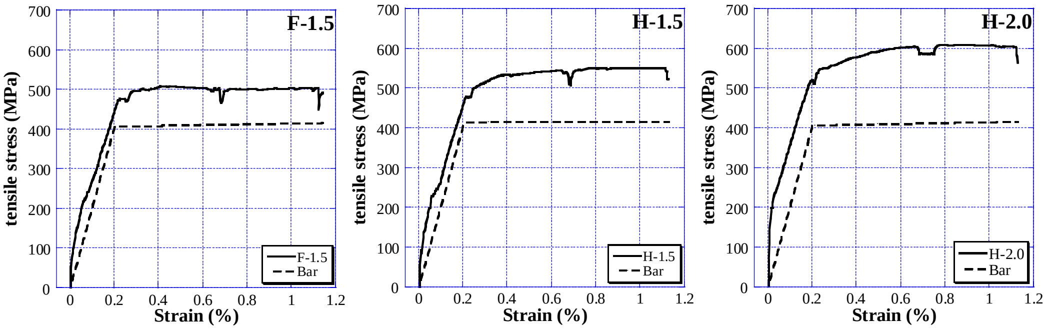


Fig.2. Stress-strain relationship counted for bar

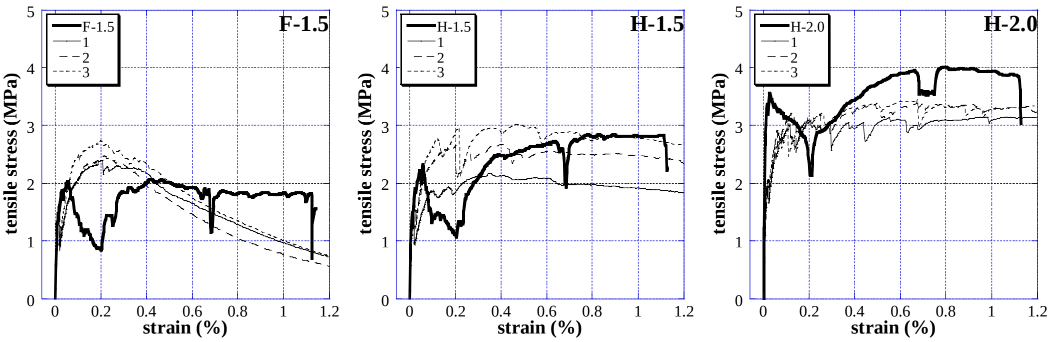


Fig.3. Relationships of tensile strain and nominal stress of matrix

In Fig. 3, three thinner curves are also shown. These were obtained by uni-axial tension tests on notched prisms (100x100x400 mm) of the matrix [5], in which the secondary flexural effect was completely eliminated [6]. In this case, water-binder ratio (W/B) was 0.45 but other conditions were same as those given in Table 2. Since localization at the weakest path finally determines the maximum stress after the multiple cracking if the matrix is not reinforced with deformed bars, the post-peak behavior of the thinner curves is less ductile, especially in case of FRCC without steel cord (F-1.5). It may mean that further development of local cracks are prevented by the deformed bar. Up to the first peak stress, the solid line and thinner lines almost overlapped each other in cases of F-1.5 and H-1.5. In case of H-2.0, however, the first peak stress was much higher than the yielding stress of the matrix. Moreover the width of the valley was much narrower than those of F-1.5 and H-1.5. It might be because bond failure around ribs was mitigated by the hybrid fiber reinforcement of higher volume content of steel cord which has sufficiently high stiffness and strength. Hence it is suggested that the hybrid fiber reinforced cement composites (especially H-2.0) may have a great potential as ductile concrete components.

Figures 4 and 5 show strain distribution in the steel bar embedded in the hybrid fiber reinforced cement composites, in which the tensile stress is the nominal stress obtained from the external force divided by the section area of the bar. In these figures, test results of plain mortar reinforced with a deformed bar is also shown as a reference. As well known, the strain in the steel bar decreases as the distance from the end increases (Fig. 4). In case of plain mortar, however, the first transverse crack initiated at 120 MPa from the notch and then suddenly the strain at the point 7 increased. On the other hand, any sudden changes of strain were not observed in cases of hybrid fiber reinforced cement composites but very ductile behavior was observed. It might be because of the multiple cracking.

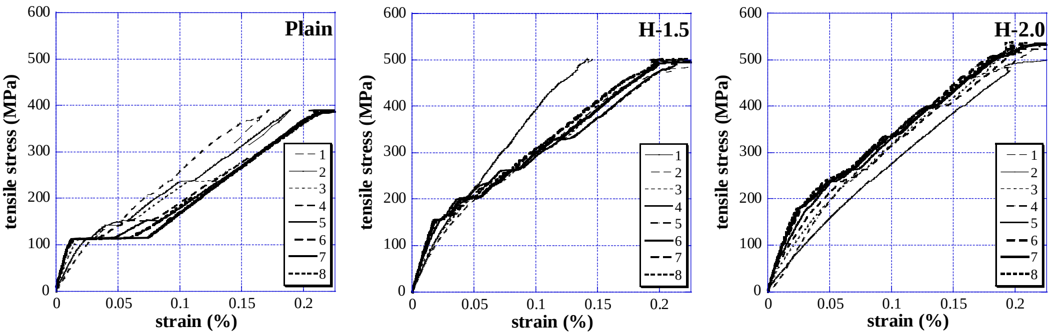


Fig.4. Strain distribution in the steel bar

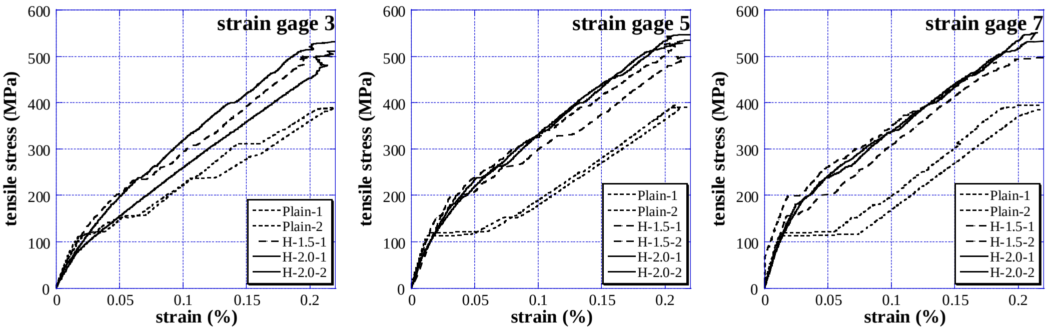


Fig.5. Strain distribution in the steel bar

4 NUMERICAL ANALYSIS OF FLEXURAL BEHAVIOR OF RC BEAM

To demonstrate the effectiveness of HPFRCC as a structural material, FEM analysis of flexural behavior of RC beam was carried out by means of ATENA 2004 developed by Cervenka et al. [7]. The configuration of the model is shown in Fig. 6. A smeared crack model was used and the complete bond was assumed. As the constitutive model under tensile stress of HPFRCC (H-2.0), a mean curve of the stress-strain relationships shown in Fig. 3 by thinner lines was employed. The compressive strength was 48.0 MPa, the tensile strength was 3.3 MPa and the Young's modulus was 15.6GPa. On the other hand, the compressive strength, the tensile strength and the Young's modulus of the normal concrete was 40 MPa, 4.0 MPa and 30.3 GPa, respectively.

Results of cracking patterns and load-displacement response are shown in Figs. 7 and 8, respectively. In Fig. 7, the local stress in the reinforcing bar and principal stress distribution are shown, too. In a very wide region, flexural cracks occurred and the steel yielded in case of the

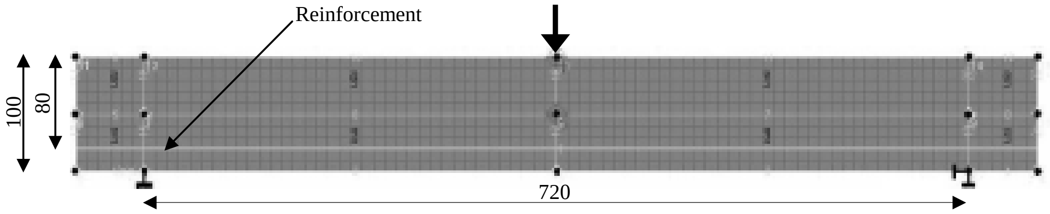
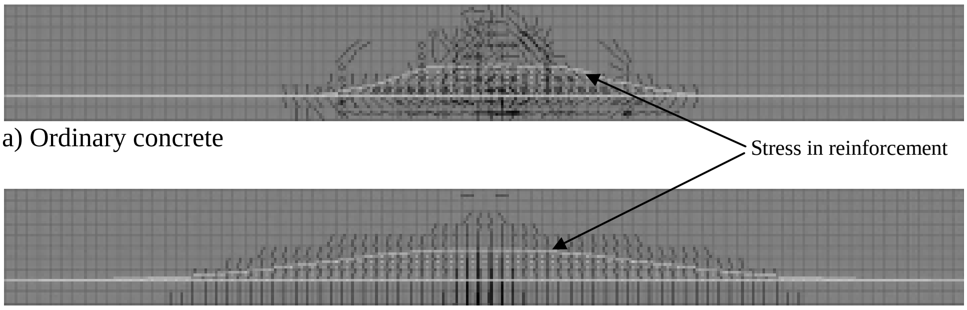


Fig.6. Configuration of model



a) Ordinary concrete

b) HPFRCC

Fig.7. Results of cracking patterns

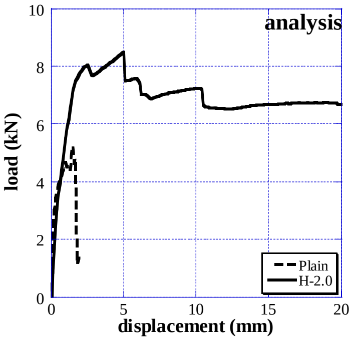


Fig.8. Load-displacement response

reinforced HPFRCC. Then a localized crack occurred at the center but the load capacity of about 80 percent of the maximum load was still kept Fig. 8. On the other hand, the yielded region in reinforcement of normal concrete beam was comparatively limited. As shown in Fig. 8, the flexural behavior of reinforced HPFRCC beam is very ductile.

5 CONCLUSIONS

Bond behavior of deformed bars embedded in HPFRCC was studied by a series of experiment. Because of the very ductile deformation characteristics of the new HPFRCC, the strain localization was drastically reduced. As the result, the bond behavior became very ductile and the maximum bond strength increased. Additionally FEM analysis of a beam under bending load demonstrated the potential capability of the new HPFRCC applied for structural components.

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