Development of a zero-span tensile test for HPFRCC used for structural repairing

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ABSTRACT: The most important characteristic of High Performance Fiber Reinforced Cement Composites (HPFRCC) is the formation of multiple fine cracks in tension, which provides novel mechanical properties, such as strain hardening behavior. For these reasons, HPFRCC can be widely used in retrofitting and repairing of existing concrete structures. In a repair application, the crack in the substrate induces localized fracture within HPFRCC. Elongation performance of HPFRCC on an existing crack, which represents resistance against the localized fracture, is required in repair applications. This research proposes the zero-span tensile test to evaluate the crack elongation performance for HPFRCC, and examines the effects of test conditions (i.e. artificial crack width, steel plate thickness, and specimen thickness) on the zero-span tensile test results. This paper also reveals that the crack elongation obtained from the test is lower than the deformation capacity evaluated by ordinary uni-axial tensile tests.

1 INTRODUCTION

In the past decade, fiber reinforced cementitious composites with higher ductility such as High Performance Fiber Reinforced Cement Composites (HPFRCC) have been developed. This progress is due to the development in fiber, matrix, and process technology, as well as better understanding of the fundamental micromechanics governing composite's behavior (Li et al., 2004).

Engineered Cementitious Composite (ECC) is one type of HPFRCC, and is designed based on fracture mechanics and micromechanics. It exhibits the ultimate strength higher than its initial cracking strength and provides multiple cracking during the inelastic deformation process, as shown in Figure 1. In conventional Fiber Reinforced Concrete (FRC), apparent softening behavior can be observed with localization after cracking. However, the deformation of HPFRCC is approximately uniform in a macro scale, and is considered as pseudo-strain hardening materials (Fisher & Li, 2004, Li 1998a).

HPFRCC promises to be used in a wide variety of civil engineering applications, as summarized in JCI (2002). In Japan, there are many applications using HPFRCC, such as seismic dampers of multi storey building, overlay repair for steel deck plate, surface repair of retaining wall deteriorated by Alkali-Silica Reaction (ASR), surface repair of irrigation channel etc. (Kunieda & Rokugo, 2006). Especially, multiple fine cracks in HPFRCC impart durability to concrete structures, because fine cracks reduce the penetration of substance (i.e. water, oxygen, chloride ion etc.) through the cracks.

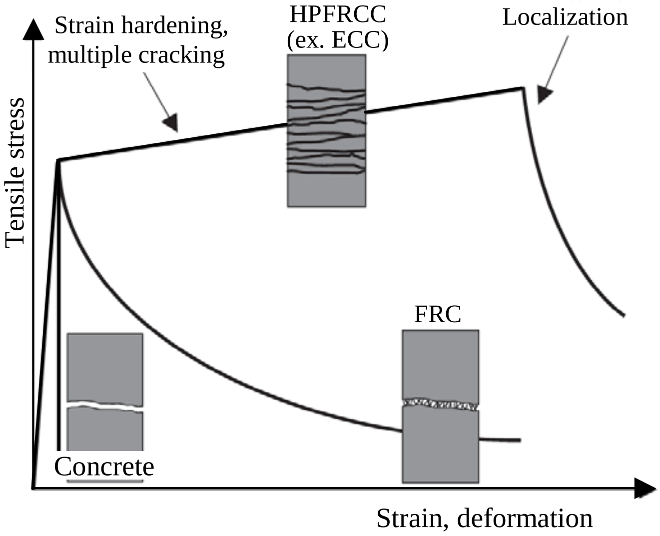


Figure 1. Tensile stress-strain behavior of cementitious composites.

Several researches subjected to the advantages of structures repaired by HPFRCC have been carried out. Lim & Li (1997) found the mechanical advantages on the interface crack trapping mechanism within HPFRCC/RC composites. Horii et al. (1998), Li (1998b), and Li et al. (2000) tried to apply HPFRCC to repair or retrofit of concrete structures, and confirmed the effect of the material ductility of repair materials on the structural performance. Kamada & Li (2000) discussed the effects of surface preparation on the fracture behavior of HPFRCC/RC composites. Kesner & Billington (2000) investigated an infill wall system using HPFRCC for seismic retrofit applications. Li (2004) addressed the required properties for repair materials to obtain durable repaired concrete structures.

The previous researches have been taken into account the advantages of high ductility of HPFRCC, which can be evaluated by uni-axial tensile tests or flexural tests. However, these tests have boundary conditions different from the existing ones in repair or retrofit applications. Kunieda et al. (2004) and Rokugo et al. (2005) showed the localized fracture of HPFRCC in patch repair systems, experimentally and analytically. One of the advantages of HPFRCC is to provide the widely distributed cracks having fine crack width. However, in repair applications having an existing crack within the substrate, crack distribution of HPFRCC was limited adjacent to the existing crack, as shown in Figure 2. In repair applications using HPFRCC, it is important to recognize the resistance against the localized fracture (crack elongation performance) in a specific boundary condition, and to evaluate the crack elongation performance of HPFRCC itself.

This paper presents the reduction in apparent ductility of HPFRCC under the special boundary condition that represent repair applications. This paper also proposes Zero-Span Tensile Test to evaluate the crack elongation performance of HPFRCC.

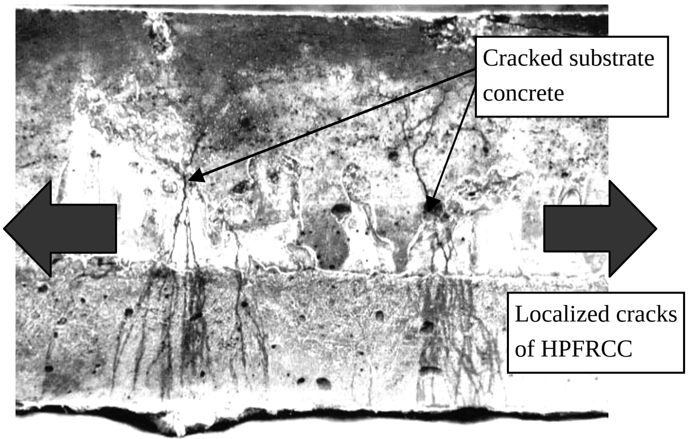
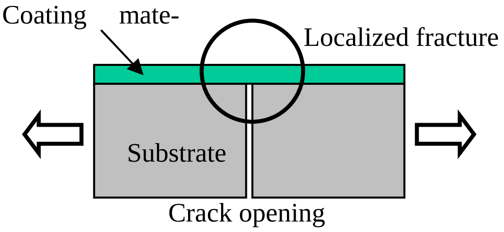


Figure 2. Localization of cracks distribution of HPFRCC adjacent to existing cracks of substrate concrete.

(a) Free film



(b) Zero-span

Figure 3. Elongation tests for surface coating materials. (Kunieda et al. 2004)

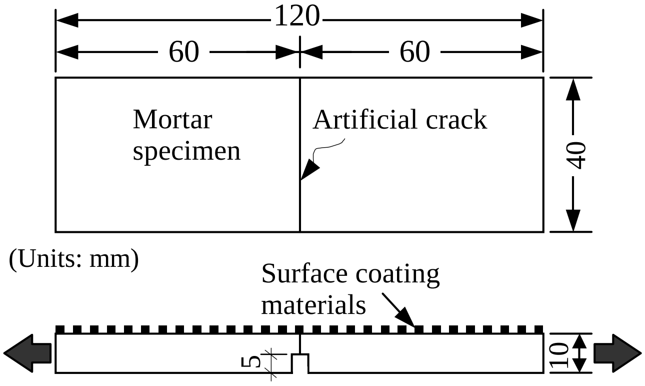


Figure 4. The test of concrete surface coating material over concrete crack. (JSCE-K-532)

2 ZERO-SPAN TENSILE TEST

The basic idea of the Zero-Span Tensile Test in this study came from the test method for surface coating materials with thin layer such as epoxy painting etc, which was specified in JSCE-K-532. Usually, the performance of the HPFRCC or other ductile materials is confirmed through tensile or bending tests with no restraint along the length of the test specimen. In surface coating repair materials evaluation should be performed not only with free film elongation tests, as shown in Figure 3 (Kunieda et al. 2004). In a deteriorated concrete structure having cracks, the deformation of the members increases as cracks open wider. It means that localized fracture occurs on the repair material near the cracks in substrate concrete. So this led to use the idea of the Zero-Span Tensile Test. The test method developed and specified to compare the material property of surface coating materials with flexibility. Because cracking of the coating material itself occurred adjacent to an existing crack, the specific boundary condition has been modeled. In the specified test method in JSCE-K-532, mortar specimens of size 120x40x10 mm are prepared. Then, a crack is induced in the mortar specimens, and each specimen half is carefully positioned, so that the artificial crack width is about 0mm. The specimen with the induced crack is repaired by a surface coating material, and uni-axial tensile tests for the specimen is conducted after the curing of the surface coating material, as shown in Figure 4. The measured displacement at the peak load is defined as the crack elongation performance of the surface coating material. As described in the previous section, the boundary condition in the repair application with HPFRCC is similar to that of this Zero-Span Tensile Test.

Table 1. Mix proportions (Kanda et al., 2005)

Water to binder ratio	Unit water (kg/m^3)	Sand by binder ratio	Shrinkage reducing agent (kg/m^3)	Fiber volume fraction (%)	Air content (%)
0.46	364	0.64	15	2	10

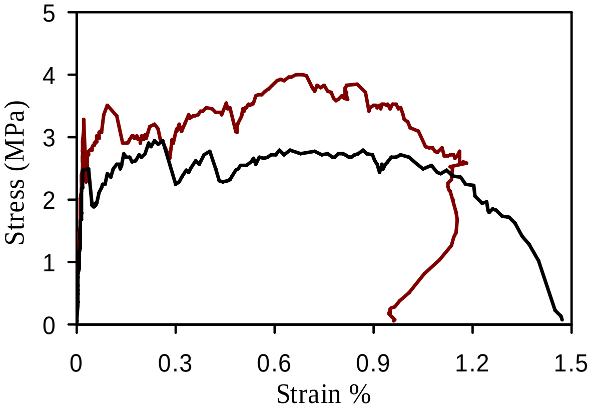


Figure 5. Stress-strain relationship of tensile test of HPFRCC-PVA with 2% PVA fiber

3 EXPERIMENTAL PROCEDURES

3.1 *Materials*

HPFRCC with Polyvinyl Alcohol fibers (HPFRCC-PVA) was used in this test. The volume fraction of fiber was 2%. The mix proportions of the HPFRCC-PVA, which is developed by Kanda et al. (2005), are shown in Table 1. The compressive strength and Young’s modulus measured by cylindrical specimens of ø100x200mm were 49.9 MPa and 18.6 GPa, respectively. By conducting uni-axial tensile tests on dumbbell-shaped specimens (tested cross section: 30x30mm), the tensile strength of the HPFRCC was 3.5 MPa and the maximum strain was approximately 0.8-1% in the gauge length of 100mm, as shown in Figure 5.

3.2 *Specimens and Test Setup*

This research proposed the zero-span tensile test using steel plates to evaluate the crack elongation performance of HPFRCC, as shown in Figure 6. The proposed test method used the steel plates not mortar as a substrate, and the steel plates and HPFRCC (repair material) was glued each other by epoxy adhesive. The other substrates such as mortar or concrete that represent similar substrate in concrete structures involve a surface preparation to obtain good bonding between HPFRCC and the substrate. However, the procedures on surface preparation impart much work to the test method. In addition, some kinds of substrate induce delamination at interface between the substrate and HPFRCC, which gives better result due to distributed cracked area widely. The influence of bond property on the crack elongation performance of HPFRCC should be removed. However, the appropriate geometry of the test specimen was neither discussed nor proposed before. In this research, three variables were examined to know their effects on the zero-span tensile test results: (1) artificial crack width, (2) steel plate thickness, (3) specimen thickness, as described in following section.

The size of the HPFRCC specimen was 100x100 mm. Combinations among the specimen thickness, steel plate thickness, and artificial crack width were adopted in this test, as shown in Table 2. Three specimens were tested in each case. In the tests, four displacement transducers were glued on both surfaces to measure the opening displacement at artificial crack (i.e. two transducers were fixed on the specimen side and the two other transducers were fixed on the steel plate side.), as shown in Figure 6. The measurement length of the transducers was

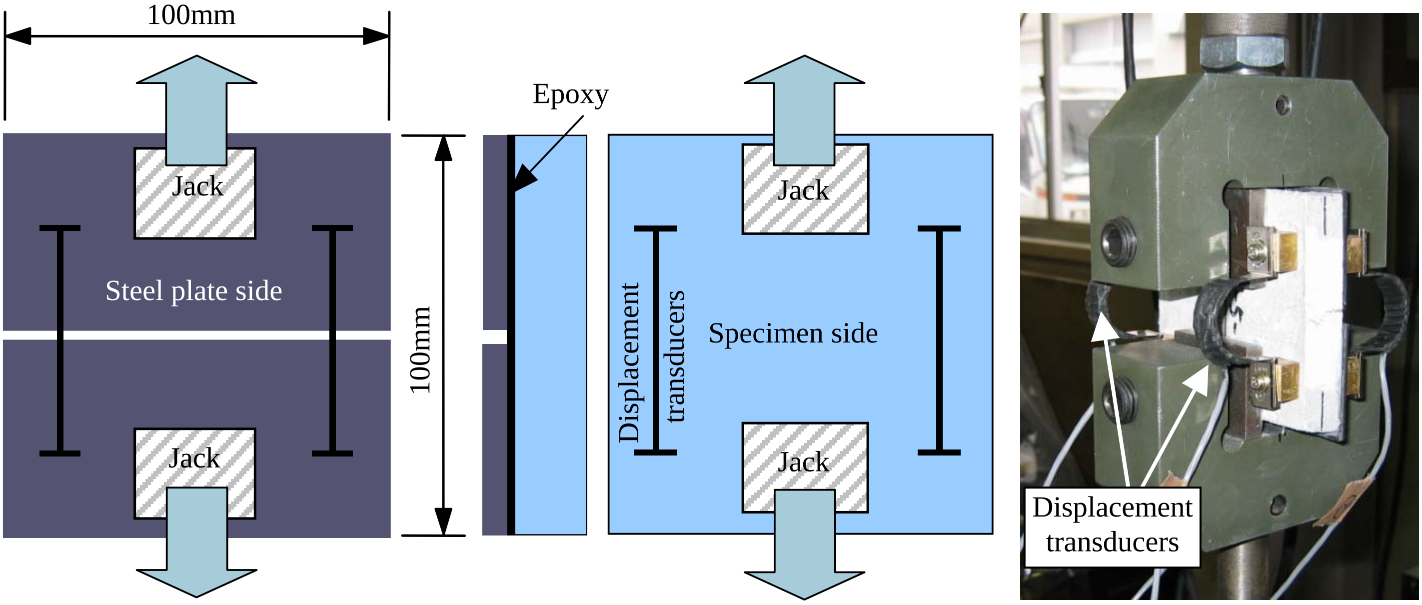


Figure 6. Test setup on zero-span tensile tests

50mm and the sensitivity of each transducer was about 1/2000mm. The loading rate was about 0.2mm/min, and the loading was terminated when the displacement was over 2mm, which was equal to the capacity of the transducers. The load was measured by load-cell having the capacity of 50kN. All tests were carried out during the age of 28-32 days.

Table 2. Tested specimens and its variables

Specimen thickness (mm)	Steel plate thickness (mm)	Artificial crack width (mm)
10	1	0, 1, 5
	3	0, 1, 5
	5	0, 1, 5
15	1	0, 1, 5
	3	0, 1, 5
	5	0, 1, 5
20	1	0, 1, 5
	3	0, 1, 5
	5	0, 1, 5

4 EXPERIMENTAL RESULTS

4.1 *Load-opening displacement relations*

Figure 7 shows examples of the measured load-displacement curves through the zero-span tensile tests, which are the averaged curves of the four displacement transducers. The legends of each graph, such as (10-3-1), represent specimen thickness (mm), steel plate thickness (mm), and artificial crack width (mm), respectively. In this study, the crack elongation is defined as displacement value at the peak load in the averaged curves of the four displacement transducers, avoiding the point of first crack load to cancel the influence of bond property on the crack elongation, as shown in Figure 7.

In these figures, slight strain hardening after the initial cracking can be observed, and HPFRCC-PVA provided crack elongation in ranging from 0.1 to 0.6mm. In the uni-axial tensile response, HPFRCC-PVA exhibited strain of about 1% at peak load, as shown in Figure 5. Each strain value obtained from

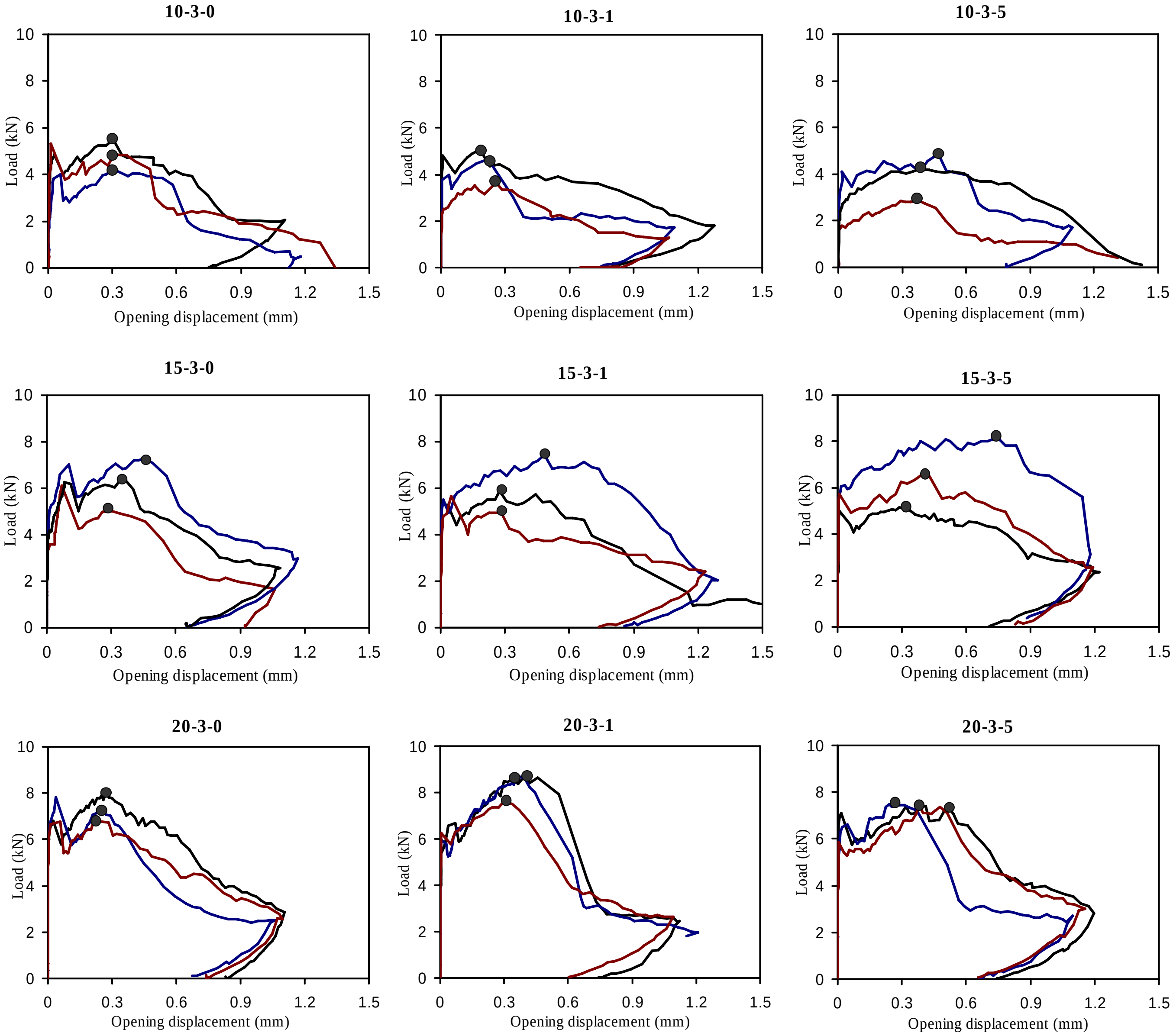


Figure 7. Examples of measured load-displacement curves from zero-span tensile tests

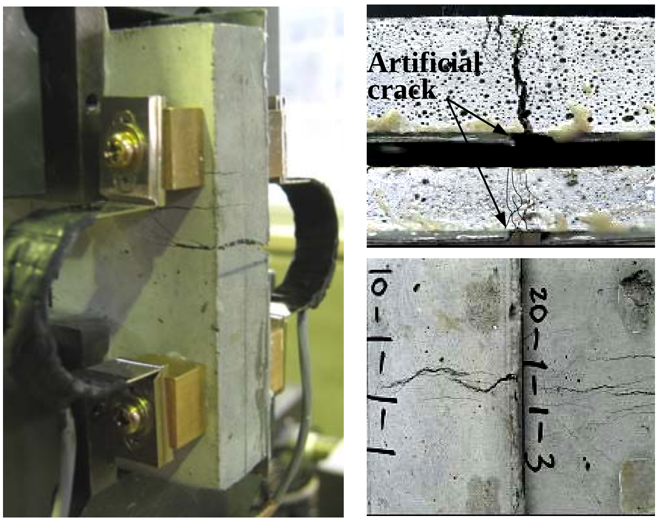


Figure 8. Examples of crack patterns on HPFRCC-PVA specimens under zero-span tensile tests.

the uni-axial tensile tests can be converted to the displacement values by means of the measurement length (i.e. 100mm). According to that, displacement at peak load in uni-axial tensile tests was 1mm.

In the results of the zero-span tensile test, most cases gave smaller displacement values than 1mm. Figure 8 shows examples of crack patterns on 10 and 20mm thickness specimens with artificial crack width of 1 mm and steel plate thickness of 1mm. As shown in these figures, localized fracture adjacent to the artificial crack can be observed. Normally, HPFRCC exhibits distributed fine cracks, which imparts ductility to the member. That means HPFRCC requires appropriate specimen shape and boundary condition to obtain the distributed cracking.

4.2 *Effects of Artificial Crack Width*

Figure 9 shows examples of crack patterns obtained in the cases of different artificial crack width. As shown in Figure 9, the number of cracks was decreased with decreasing the artificial crack width.

Figure 10 shows the relationship between crack elongation and artificial crack width, in the case of the specimen thickness of 10mm and 20mm. The legend of each figure shows the specimen thickness and steel plate thickness, respectively. The obtained crack elongation became smaller with decreasing the artificial crack width. That is due to the number of allowed cracks increases around the artificial crack region by increasing the artificial crack width. The crack elongations of the specimen with artificial crack width of 0mm were in ranging from 0.2mm to 0.5mm. However, artificial crack widths of 1mm and 5mm do not reflect the existing crack width in concrete structures for repair. As proposed in ordinary standard test method (JSCE-K-532), artificial crack width of 0mm might be useful for crack elongation of HPFRCC.

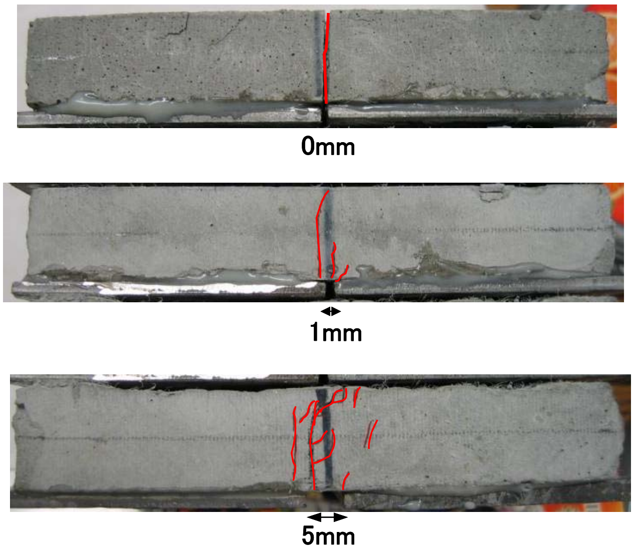
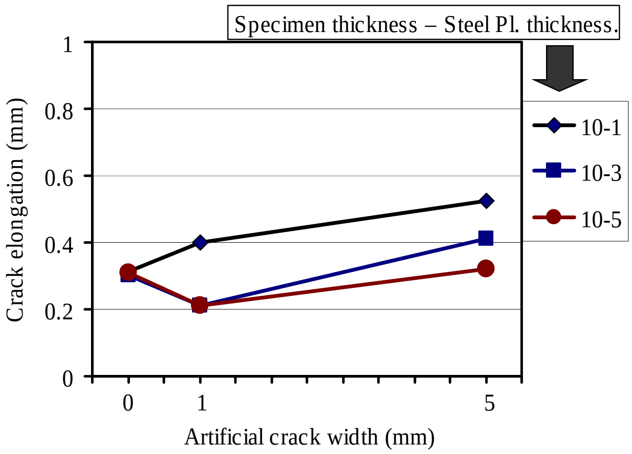
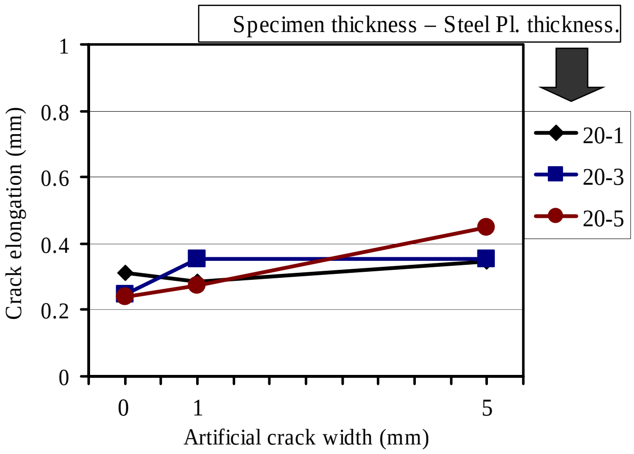


Figure 9. Effect of artificial crack width on the number of allowed cracks.



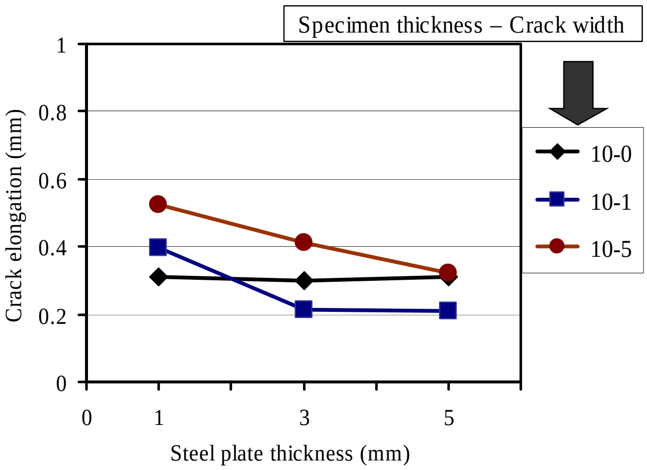
a) Case of specimen thickness of 10mm.



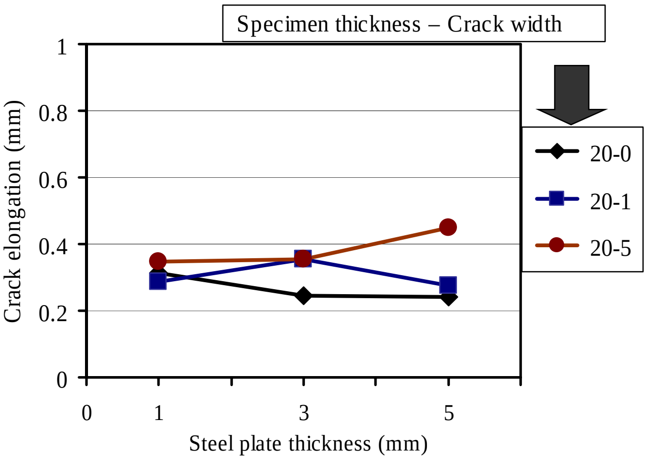
b) Case of specimen thickness of 20mm.
Figure 10. Effect of artificial crack width on the crack elongation through zero-span tensile test.

4.3 *Effects of Steel Plate Thickness*

Figure 11 shows the relationship between crack elongation and steel plate thickness, in the case of the specimen thickness of 10mm and 20mm. The legend shows the specimen thickness and artificial



a) Case of specimen thickness of 10mm.



b) Case of specimen thickness of 20mm.

Figure 11. Effect of steel plate thickness on the crack elongation through zero-span tensile test.

crack width, respectively. There are two typical behaviors either increasing the crack elongation with increasing the steel plate thickness, or decreasing the crack elongation with increasing the steel plate thickness. No significant tendency can be observed through the tests. It seems that both the stiffness and thickness of HPFRCC and the steel plate affect the deformation of the composite in tension. However, the results using the steel plate thickness of 3mm provided similar results in both 10mm and 20mm cases.

4.4 *Effects of Specimen Thickness*

Figure 12 shows the relationship between crack elongation and specimen thickness, in the case of the steel plate thickness of 3mm. The legend shows the steel plate thickness and artificial crack width, respectively. There is no influence of the specimen thickness on the crack elongation in this test. It was clarified that the specimen size in ranging from 10 mm to 20 mm can be applied to the zero-span tensile test.

In the future, specimen thickness, which reflects the thickness of repaired layer, should be used.

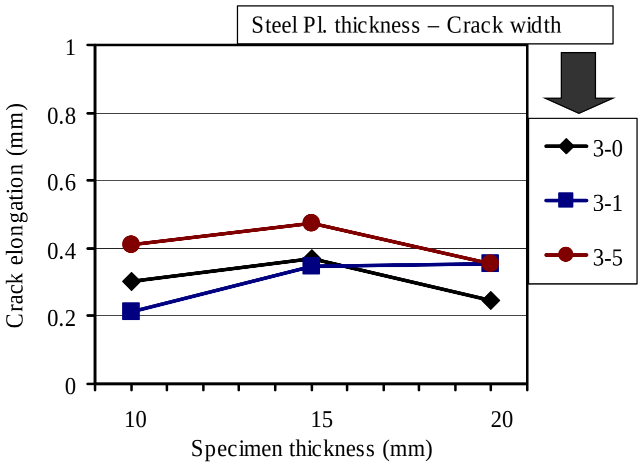


Figure 12. Effect of specimen thickness on the crack elongation through zero-span tensile test.

5 CONCLUSIONS

(1) The evaluated crack elongation through Zero-Span Tensile Tests is much smaller than that of deformation capacity in ordinary uni-axial tensile tests. That is because a localized cracking can be observed adjacent to the artificial crack in this test. These results show that evaluating the crack elongation performance of HPFRCC through the zero-span tensile tests is quite important for repairing applications.

(2) The influence of both steel plate thickness and specimen thickness on the crack elongation was not significant. However, the obtained crack elongation became smaller with decreasing the artificial crack width.

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