Invited paper

Recent Progress on HPFRCC in Japan
Required Performance and Applications

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Abstract

High Performance Fiber Reinforced Cement Composites (HPFRCC) show multiple cracking and strain-hardening behaviors in tension. Current applications in Japan include bridge decks, building dampers, retaining wall, irrigation channels and so forth. While the novel properties of HPFRCC are well known, the required performance and its criteria have not been clarified. For example, in addition to tensile load bearing capacity, protection against penetration of substance through fine cracks is also important. Clarification of the required performance and its criteria for HPFRCC is important to evaluate the design concepts of each application. This paper introduces recent applications using HPFRCC in Japan, focusing on required performance.

1. Introduction

High Performance Fiber Reinforced Cement Composites (HPFRCC), which contain synthetic and/or metallic short fiber, show multiple cracking and strain-hardening behaviors in tension. One type of HPFRCC is Engineered Cementitious Composites (ECC), which was developed by Li (1993). **Figure 1** shows an image of the material response of HPFRCC under uniaxial tension. When a large number of cracks are densely distributed as illustrated in **Fig. 2**, the deformation is macroscopically regarded as uniform. In the process of strain softening, deformation is localized by increases in the width of only a limited number of cracks. A lot of research for the evaluation and improvement of material properties, and the development of process technology, design concepts and ideas for applications has been performed (Kanda 2003; JSCE 2005 a; JCI 2002 a).

A Research Committee on Ductile Fiber Reinforced Cementitious Composites was established within the Japan Concrete Institute (JCI) (April 2001 to March 2004) to investigate such ductile materials and their structural uses (JCI 2003a). The committee introduced ductile materials including HPFRCC to Japan through round robin tests subject to various kinds of uniaxial tensile tests and bending tests (Kanakubo 2006). Ordinary ductile cement composites are classified by performance, as shown in **Fig. 3** (JCI 2003b). In addition to HPFRCC, DFRCC includes a group of FRCCs that exhibit multiple cracking in bending only. The Research Subcommittee on Fiber Reinforced Mortar with Multiple

Cracks, which operates within the Concrete Committee of the Japan Society of Civil Engineers (JSCE) (Sep. 2004 to Sep. 2006), has investigated the evaluation and utilization methods of HPFRCC, and summarized the
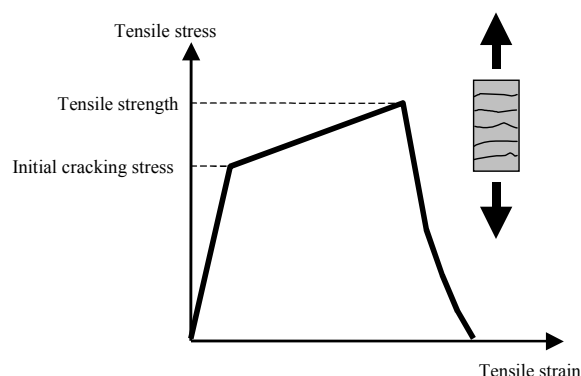

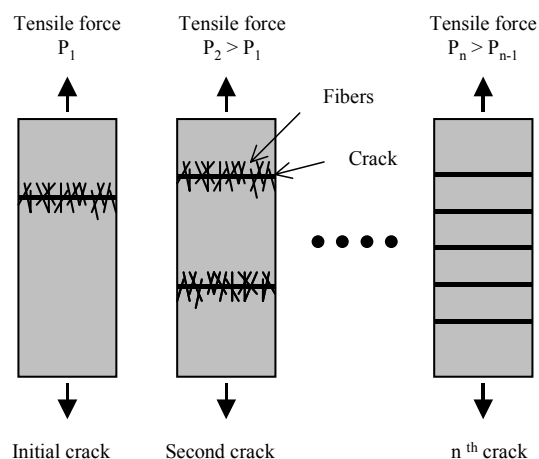Fig. 1 Tensile stress-strain relationship.

Fig. 2 Multiple cracking.

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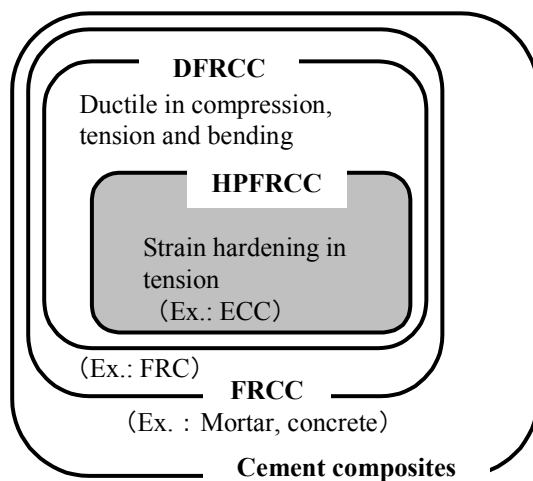[2]Professor, Department of Civil Engineering, Gifu University, Japan.

Fig. 3 Classification based on ductility of cement composites (JCI 2003b).

Table 1 Tentative contents of JSCE recommendations (draft).

1 General
2 Basis of Design
3 Design Values for Materials
4 Load
5 Structural analysis
6 Verification of Structural Safety
7 Verification of Serviceability
8 Verification of Fatigue Resistance
9 Structural details
10 Verification of Durability
11 Steel-HPFRCC composites
12 Constructions through Casting
13 Constructions through Spraying
Appendix

committee report (JSCE 2005a). As the establishment of recommendations, guidelines or a manual is always useful for the application of new materials such as HPFRCC to existing structures, the JSCE will publish a recommendation titled Design and Construction of HPFRCC Structures (Draft), which reflects the existing applications, trial tests and fundamental research, in 2006. The tentative contents of the recommendation are tabulated in **Table 1**.

This paper introduces recent applications using HPFRCC in Japan focusing on required performance, referring to the committee report (JSCE 2005a).

2. Required performance for structures with HPFRCC and its evaluation

Novel properties of HPFRCC such as strain hardening and multiple cracking are well known. The material should be applied appropriately, based on the perform-

ance requirements for structures. **Table 2** shows the example of some relationships between required performance and applications. Performance based on multiple fine cracks is mainly required, because greater durability of concrete structures is increasingly becoming a requirement in Japan, and reducing crack width is one of the approaches to obtain more durable concrete structures. On the other hand, it is difficult to use structural response obtained from novel mechanical properties of HPFRCC because of the lack of design concepts that take deformation capacity into consideration.

Specific HPFRCC requirement criteria and its testing methods for strain and other parameters have not yet been defined. The following sections briefly discuss the

Table 2 Example of required performance and application (in Japan).

		Using mechanical properties of HPFRCC			Using multiple fine cracks of HPFRCC				Fundamentals		
		Tensile capacity (energy absorption)	Fatigue	Bond property	Elongation on a crack	Protection against penetration of substance	Aesthetics	Repair minimization	Durability	Size stability (shrinkage)	Erosion
Bridge decks		○	○	○		○					
Building dampers		○						○			
Surface repair	Dams			○	○	○	○		○	○	○
	Irrigation channels			○	○	○	○				○
	Retaining walls			○	○	○	○				
	Viaducts		○	○	○	○	○				

examples of required performance for the structures with HPFRCC to provide a basis for the evaluation of design concepts of each application. Although performance related to impact resistance and ductility in compression of HPFRCC might be important, it will not be discussed because of no application concerning the performance in Japan.

2.1 Tensile stress strain relationship and energy absorption

The tensile load bearing capacity of HPFRCC, which is one of the advantages in a structural use, should be evaluated appropriately. Although the required performance related to deformation has not been clarified, higher energy consumption of members with HPFRCC having critical strain similar to yield strain of reinforcement is expected.

To identify the shape of the tensile stress strain relationship, various kinds of uniaxial tensile tests each using different specimen sizes, geometries and boundary conditions have been proposed and carried out (Matsuo and Kanda 2002). In fiber reinforced materials including HPFRCC, fiber orientation is strongly affected by the specimen geometry and the process technology, such as placement or spraying (thin specimens, spraying techniques or extrusion molding result in a two-dimensional fiber orientation) (Takashima *et al*. 2003; Kunieda 2002). Therefore, the tensile properties used in design should reflect the actual conditions of applications. Alternatively, if test results obtained under conditions different from existing conditions are used, the relation between the test and existing conditions should be carefully verified.

The modeled bi-linear stress strain relation shown in **Fig. 4** is proposed for the tensile stress strain relation of HPFRCC (JSCE 2005a). To determine the modeled stress strain relations, initial cracking strength and strain at tensile strength are proposed as specific values in the JSCE recommendation (draft), where initial cracking strength is divided by material factor 1.3. **Figure 5** shows the stress and strain distributions within the cross sections of HPFRCC members, compared with those of
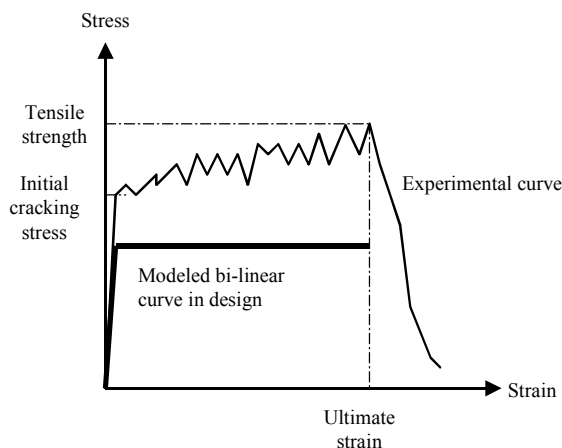
RC. One is the members consists of HPFRCC, and the other is a composite member such as those used for overlay repair or patch repair systems. In calculations of load bearing capacity against bending moment, the tensile stress of HPFRCC at each strain level helps to provide higher load bearing capacity, assist reinforcement, or give higher fatigue resistance, for both serviceability and structural safety.

To use the higher energy consumption of HPFRCC in tension expressed by the strain hardening behavior, structural elements to control the behavior of concrete structures, such as seismic dampers and connection elements, has been proposed (Fukuyama *et al*. 2003, Kesner *et al*. 2003, Maruta *et al*. 2005). **Figure 6** shows the typical structural response of RC beams and HPFRCC subject to cyclic loading (Fukuyama *et al*. 1999, JCI 2002b). Higher energy consumption in the HPFRCC member, which reduces the damage of the structure itself, can be observed. In addition, a reduction in crack width for each crack can be also obtained by the multiple cracking mechanism of HPFRCC. Minimal repair work after severe loading may also be required for this structural system.

2.2 Fatigue resistance

The novel tensile properties of HPFRCC described in the previous section also result in higher fatigue resistance. Good results obtained from laboratory tests have been reported (Li *et al*. 1998; Suda *et al*. 2001; Matsumoto 2003). Matsumoto (2003) shows fundamental fatigue properties through bending tests of PVA-ECC and PE-ECC. These materials are one type of HPFRCCs. Concerning S-N relations, both HPFRCCs give a bi-linear relationship on a semi-log plot, whereas ordinary FRC gives a linear relationship on an S-N plot. The paper shows that HPFRCC has longer fatigue lives at higher fatigue stress levels. However, HPFRCC has shorter fatigue lives than ordinary FRC at lower fatigue stress levels, because only a few cracks can propagate in the specimen. The cracking state under fatigue load is an important factor for fatigue resistance of HPFRCC. Further discussions and more experimental data are needed to design the fatigue resistance.

2.3 Bonding within HPFRCC composites

Two kinds of composite systems using HPFRCC are proposed, as follows:
- HPFRCC/RC composites
- HPFRCC/steel composites

The bond property between the HPFRCC and substrate concrete in HPFRCC/RC composites is one of the important performance. Good bonding performance is required to obtain larger deformation of both materials uniformly. Another aspect is the hazard to third parties (i.e. falling off of cover concrete). Thus, improvement of performance related to hazards for third parties is strongly required for all infrastructures in Japan. The large deformation capacity of HPFRCC reduces such risk

Fig. 4 Modeled stress-strain curves in design.

Concrete

Rebar

Cross section   Strain distribution   Stress distribution

Comp. stress (concrete)

Tens. stress (rebar)

(a) Images of strain and stress distribution of ordinary RC member in ultimate state
(Tensile stress of concrete is neglected)

HPFRCC

Rebar

Cross section   Strain distribution   Stress distribution

Comp. stress (HPFRCC)

Tens. stress (HPFRCC)

Tens. stress (rebar)

(b) Images of strain and stress distribution of HPFRCC member in ultimate state
(Tensile stress of HPFRCC is considered)

Concrete

HPFRCC

Rebar

Cross section   Strain distribution   Stress distribution

Comp. stress (concrete)

Tens. stress (HPFRCC)
Tens. stress (rebar)

(c) Images of strain and stress distribution of repair system in ultimate state
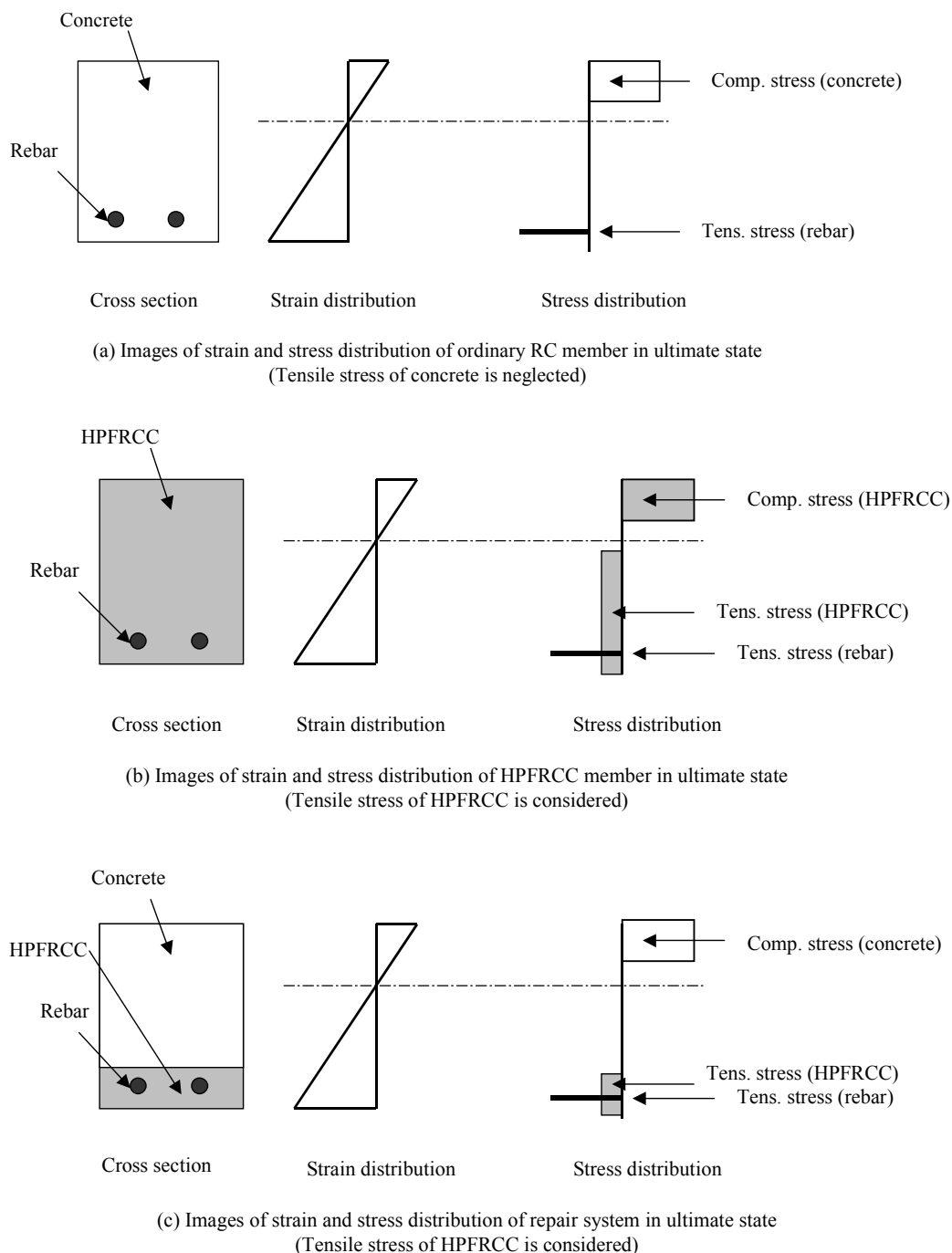(Tensile stress of HPFRCC is considered)

Fig. 5 Calculation of bending moment of beams with or without HPFRCC.

(Kanda *et al.* 2003). Evaluation of performance including shear bond behavior at the interface is quite difficult. In addition, required criteria for the performance have not been clarified. Therefore, for simplicity's sake, uniaxial bond tests were adopted as evaluation tests of patch repair materials in the JSCE specification (JSCE 2005b), as shown in **Fig. 7**.

When two kind of materials each having different deformation capacity (e.g. HPFRCC and RC) are com-

bined as structural members, good bonding imparts a constrained boundary to the material with the larger deformation capacity. This means that ductility of HPFRCC is restricted by the specific boundary condition. In HPFRCC/RC composites, it should be noted that good bonding between the HPFRCC and substrate might reduce crack distribution. This behavior and its evaluation will be discussed in the next section.

In HPFRCC/steel composites, good bonding is re-
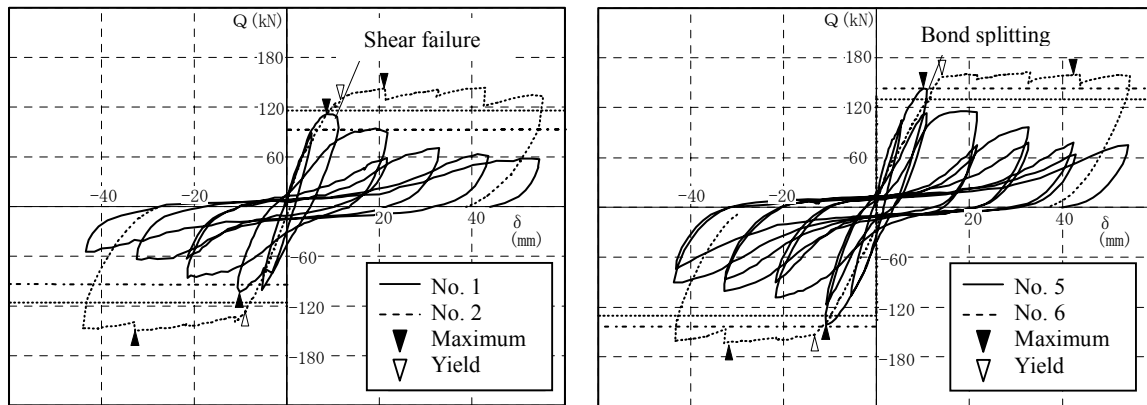
(a) Load-displacement curves
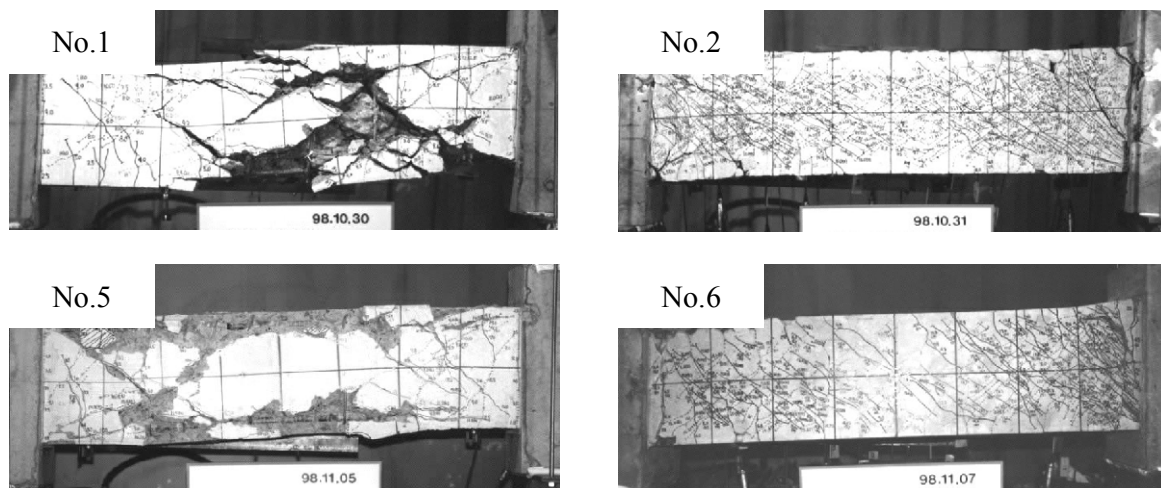
(b) Crack patterns (final)

Fig. 6 Shear failure behaviors of RC and HPFRCC (Fukuyama et al. 1999).

quired to obtain larger deformation of both materials uniformly. A typical example is shown in **Fig. 8**. This composite consists of HPFRCC and a steel pipe with and without bonding, each having ribs or no ribs, respectively (Rokugo *et al*. 2002). Good bonding between the HPFRCC and steel pipe results in narrow crack intervals within the members, and higher load bearing capacity. Another typical composite is reinforcement (rebar) covered with HPFRCC. Fischer (2002) investigated compatible deformation between HPFRCC and steel reinforcement. Here, compatible deformation gives lower interface shear stress and reduces splitting and/or spalling of cover concrete. Larger critical strain of the HPFRCC that equals yielding of reinforcement may achieve uniform multiple cracking among members.

2.4 Elongation of existing crack
In overlay or patch repair systems, existing cracks may be observed in the substrate concrete. External loads cause larger crack width movement. **Figure 9** shows

analytical crack patterns demonstrating elongation of an existing crack (Kunieda *et al*. 2004). In the case of the brittle repair material, the elongation consists of a single crack. In contrast, HPFRCC produces distributed cracks within a narrow area. This shows that only bonded HPFRCC around the crack deformed locally and then cracked. When an unbonded region adjacent to the interface is formed, a wider crack distribution is observed, as illustrated in **Fig. 9**. Evaluating the elongation on an existing crack within HPFRCC composite is important, because material properties (ductility) of HPFRCC with and without constraint are different.

For surface coating materials (paint type), the JSCE Standard (JSCE 2002) specifies zero-span tensile tests, as illustrated in **Fig. 10**. This type of test should be developed in the near future for HPFRCC.

2.5 Protection against penetration of substance
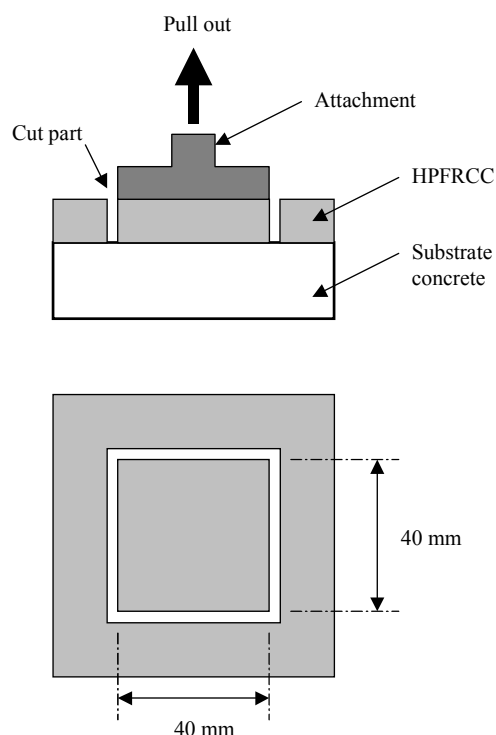Because the materials used in HPFRCC is similar to those of ordinary cement mortar, evaluation of penetra-

Fig. 7 Uniaxial bond strength tests for patch repair materials.

(a) Mortar specimen

(b) ECC specimen without ribs

(c) ECC specimen with ribs

Fig. 8 Cracking behavior of steel pipe covered with HPFRCC (Rokugo et al. 2002).

tion of substances for HPFRCC before cracking can be done using the same evaluation and estimation tools as those used for ordinary mortar.

For HPFRCC after cracking, one of the advantages of HPFRCC is the formation of fine cracks. Some research on the effect of fine cracks on penetration of substances such as oxygen, water, chloride ions, and carbon dioxide has been done (Suda and Rokugo 2005; Hiraishi *et al*. 2005). Further, multiple cracking with fine cracks imparts corrosion mechanism changes to the rebars within the HPFRCC (Hiraishi *et al*. 2005). Rebars within the HPFRCC are corroded not through macro-cell corrosion with a fast corrosion rate but through micro-cell corrosion with a slow corrosion rate.

2.6 Aesthetics
One of the attractive performance of HPFRCC is aesthetics. In ordinary concrete structures, cracking causes a degradation of aesthetic appearance in the form of clearly visible cracks, which is compounded by soiling (staining) of the concrete surface. In contrast, HPFRCC exhibit only fine cracks that do not stand out from a distance. It should be noted, however, that visual observation of concrete structures is widely employed for ordinary maintenance inspections of concrete structures, and therefore the influence of smaller crack widths on the maintenance of structures with HPFRCC should be discussed from the viewpoint of visual inspections.

2.7 Other fundamental performance
(1) Durability of material itself without cracks
Durability is an important performance factor required for construction materials including HPFRCC. Deterioration of the material itself due to frost attack (freeze-thaw), alkali-silica reaction, or chemical attack should be estimated appropriately. As the materials used in ordinary HPFRCC, such as Portland cement and sand, are similar to those used in ordinary cement mortar, it is likely that material performance estimation approaches for mortar and/or concrete can be applied to HPFRCC (e.g. Standard Specifications for Concrete Structures–2001 "Maintenance", JSCE).

(2) Size stability (shrinkage)
HPFRCC potentially have shrinkage strain because of the use of fine materials such as cement and admixture. Some research has been done on the shrinking properties and shrinkage cracking of HPFRCC (Bolander *et al*. 2003; Li 2005). Basically, material with no shrinkage or other countermeasures to reduce shrinkage should be used, because HPFRCC are often applied to composites with a constraint (composite system). Although the width of a shrinkage crack is quite small in HPFRCC, tensile stress induced by the shrinkage may reduce the tensile load bearing capacity. The testing method using an em-
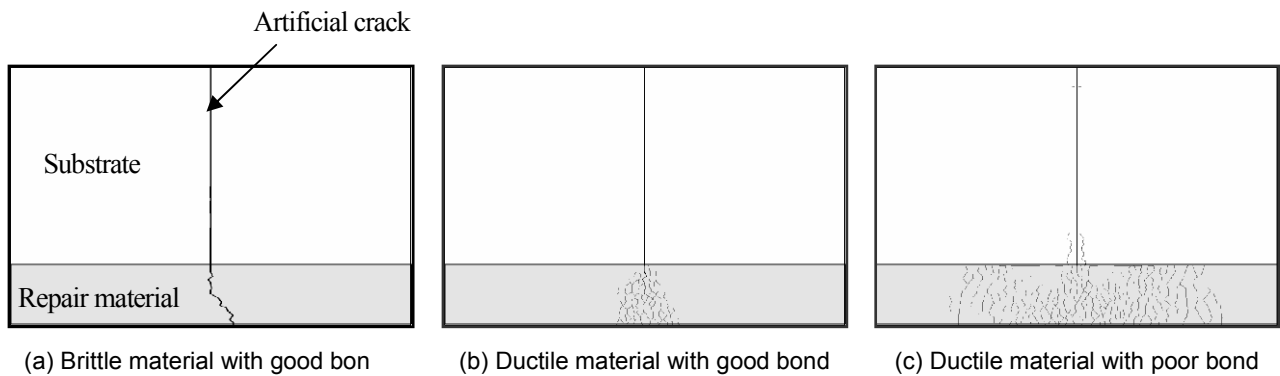
Artificial crack

(a) Brittle material with good bon   (b) Ductile material with good bond   (c) Ductile material with poor bond

Fig. 9 Crack patterns considering elongation around a crack (Kunieda et al. 2004).

Substrate (mortar)   Surface coating material
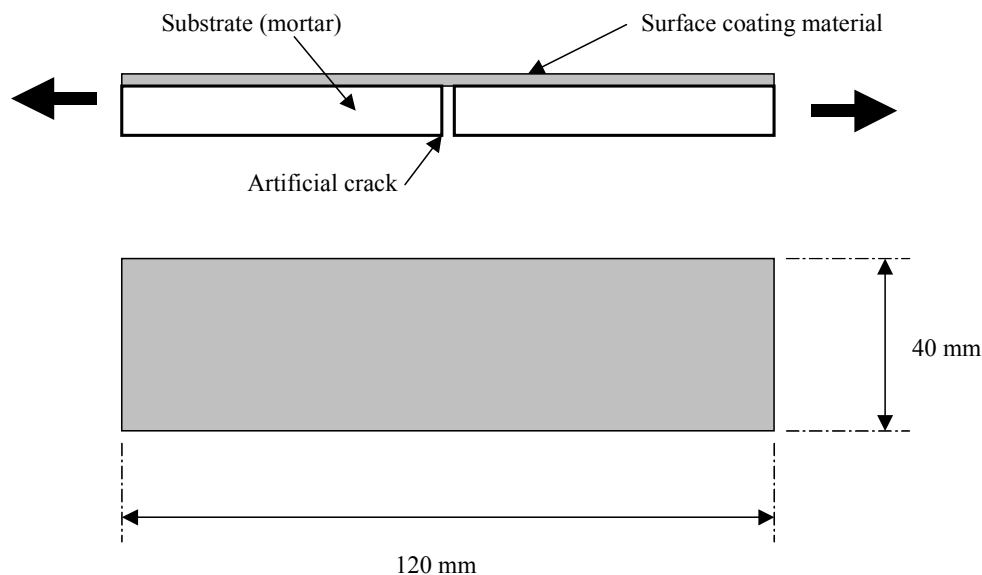
Artificial crack

40 mm

120 mm

Fig. 10 Zero-span tensile tests for surface coating materials (JSCE K-532-1999).

bedded strain gauge that is applied to ordinary concrete is helpful for evaluating the shrinkage properties of HPFRCC.

(3) Erosion
Good resistance against erosion can be expected from HPFRCC containing short fiber. In the case of ordinary fiber reinforced concrete, Koyanagi *et al.* (1988) found that the short fiber content imparts higher resistance against erosion in FRC specimens. No research on evaluation methods and testing methods for erosion of HPFRCC has been done, and such research is called for.

3. Recent applications in Japan

Recent applications of HPFRCC in Japan take advantage of the superior mechanical properties and fine cracking mode of such composites, as described in **Table 2**. Ap-

plications in Japan include the following:
- Bridge decks to improve fatigue resistance through tensile force bearing capacity of HPFRCC
- Dampers in reinforced concrete buildings to increases energy absorption and suppress vibration during earthquakes, in addition to minimizing repair after severe loading
- Surface repair of dams and irrigation channels to improve shielding properties of deteriorated concrete surfaces
- Surface repair of retaining walls deteriorated by alkali silica reaction to improve aesthetic appearance
- Surface repair of viaducts for carbonation retardation

3.1 Bridge decks
Since HPFRCC can bear tensile forces, members made of HPFRCC in combination with steel plates provide higher flexural resistance with a thinner cross section than normal steel-concrete members. **Figure 11(a)** shows

(a) Overview of bridge

(b) Adopted plate-type dowels

(c) Placement of HPFRCC

Fig. 11 Outline of Mihara Bridge (Mitamura et al. 2005).

Mihara Ohashi in Hokkaido with a bridge length of 972 m and central span of 340 m (Mitamura 2005). In 2004, half the depth of the asphalt overlay on the steel deck of this bridge was replaced with 40 mm thick HPFRCC to increase the load bearing capacity and stiffness of the decks while reducing the stress generated, thereby improving the fatigue resistance of the stiffener for the steel deck. This became necessary because the requirements for fatigue resistance in the standard specifications were revised while the bridge was under construction.

Plate-type dowels as shown in **Fig. 11(b)** were adopted to ensure the bond between the HPFRCC and the steel deck (Fukuda 2004). HPFRCC was mixed at ready-mixed concrete plants, hauled to the construction site by large agitating trucks, and subjected to secondary mixing at the construction site. Approximately 30 m^3 of HPFRCC were placed each day, with the amount of mixed HPFRCC totaling approximately 800 m^3. The

placing process is shown in **Fig. 11(c)**.

3.2 Dampers for buildings

An HPFRCC member reinforced with steel bars is capable of absorbing a large amount of energy under alternate loading. As shown in **Fig. 12**, HPFRCC members were incorporated as dampers in reinforced concrete buildings in Tokyo and Yokohama in 2004 and 2005, respectively (Maruta *et al.* 2005). The HPFRCC members were connection elements with main (core) frames of high-rise buildings, and the elements involved both higher energy consumption and minimized repair work after earthquake. To design the elements considering structural response, shear tests using 1/2.5 scale specimens were conducted. The test results show that the elements have novel structural performance and narrow crack width (smaller than 0.3 mm) after cyclic loading.

(a) Applied building (perspective)   (b) Structural member made of HPFRCC

Fig. 12 Outline of damper in building (Maruta et al. 2005).

3.3 Surface repair of dams

The shielding performance of HPFRCC is excellent owing to its small crack widths, which minimize water permeation. The dam height of Mitaka Dam (Kojima 2004), a gravity concrete dam in Hiroshima Prefecture, was increased from approximately 33 m to 44 m by placing new concrete onto the existing dam body on the downstream side (**Fig. 13**). In 2003, 30 m^3 of HPFRCC was sprayed on the upstream dam surface (area: 500 m^2) with a thickness of 30 mm, to improve the shielding performance of the deteriorated existing concrete surface (**Fig. 13**). Anchors were driven at 1.5 m^2 intervals to ensure a strong bond between the substrate and HPFRCC.
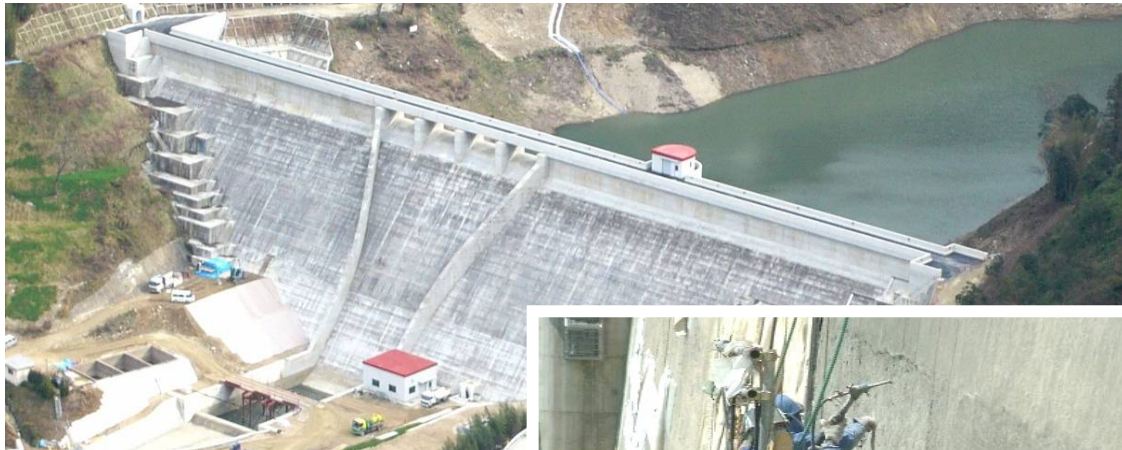
3.4 Surface repair of irrigation channels

Many irrigation channels suffer deterioration due to abrasion, having been in service for several decades. The Central Main Channel (JSCE 2005a) (side wall height: 1.1 m, bottom slab width: 1.5 m) in Shiga Prefecture, shown in **Fig. 14**, was so deteriorated that coarse aggregate was exposed on the surfaces and the edges were

partially lost, with cracks approximately 1 mm wide and approximately 1m long. At Seridanno Channel in Toyama Pref. (side wall height: 1.1 m, masonry side wall height: approx. 2.4 m, bottom slab width: approx. 2.05 m), coarse aggregate was exposed on the surfaces and the bottom slabs were partially spalled off. Part of the filling mortar at the bottom of the masonry sidewall was also lost.

A water jet was used for substrate treatment to remove deteriorated mortar. Each masonry joint in the sidewalls of the Seridanno Channel was filled with mortar. HPFRCC was troweled and sprayed at the Central Main Channel and Seridanno Channel, respectively, in 2005. (thicknesses of 6 and 10 mm for sidewalls and bottom slabs, respectively.) Spraying resulted in a work speed two to three times higher than that of troweling.

Conventional repair mortar and ultrahigh strength polymer cement mortar were also used at the Central Main Channel for comparison with HPFRCC. Cracks were observed in conventional mortar and ultrahigh strength polymer cement mortar one month after application, whereas no cracking was found in HPFRCC.

(a) Overview of Dam

(b) Spraying

Fig. 13 Surface repair of concrete dam (Kojima et al. 2004).

（a）Before repair

（b）Surface preparation

（c）Trowel

（d）After repair

Fig. 14 Surface repair of concrete irrigation channel (trowel).

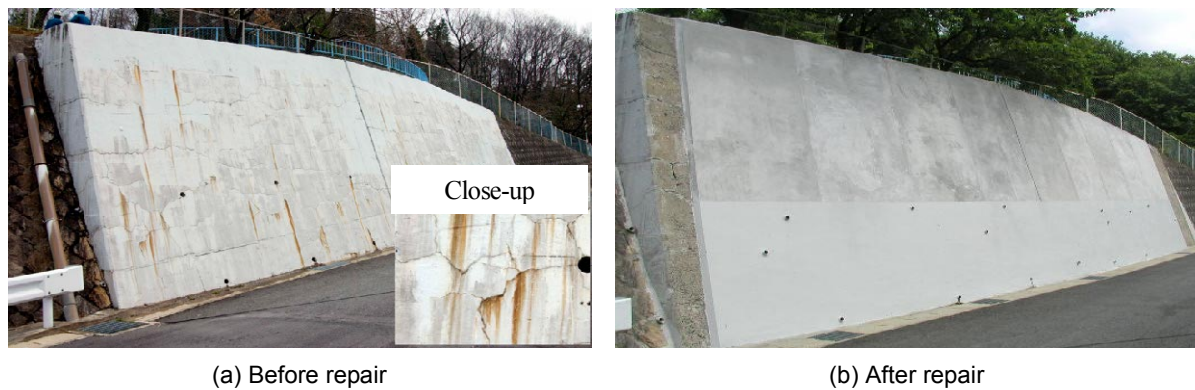(a) Before repair   (b) After repair

Fig. 15 Surface repair of concrete retaining wall (Rokugo et al. 2005).

Table 3 Conditions for the trial application of retaining wall.

Repair materials	Block No.	Reinforcement	Bondless are at crack
Repair material A	1	Welded bar mesh	None
Fiber: PVA+ High strength PE	2	Expanded metal	None
Volume fraction of fiber: 1.5%	3	None	None
Matrix: Premixed polymer cement mortar	4	None	Present
Repair material B	5	Welded bar mesh	None
Fiber: High strength PVA	6	Expanded metal	None
Volume fraction of fiber: 2.1%	7	None	None
Matrix: Premixed cement mortar	8	None	Present
Repair material C Fiber: None Matrix: Premixed cement mortar	9	Welded bar mesh	None
No-repaired	10	None	None

### 3.5 Surface repair of retaining walls

Because of its small cracking widths, HPFRCC is suitable for application on the surface of cracked concrete structures in terms of aesthetics. A gravity concrete retaining wall in Gifu Prefecture measuring approximately 18 m in width and 5 m in height was constructed in the 1970s. As cracks due to alkali-aggregate reaction developed in the wall, these cracks were injected with epoxy resin and the wall surface was coated with an organic material in 1994. When the surface repair material also cracked, the wall was subjected to surface repair using sprayed HPFRCC and other materials (Rokugo *et al.* 2005) in 2003, as shown in **Fig. 15** and **Table 3**. The wall was divided into nine repaired sections and one no-repaired one. These were combinations of three repair materials (two HPFRCCs and one repair mortar), three reinforcement levels (welded wire mesh, expanded metal, and no reinforcement), and two crack treatment levels (with and without sealing to increase the bondless areas). The wall surface was chipped off using a water jet. Acrylic resin coating was applied to the repaired surface in the area from the bottom of the wall to a height of 2 m. The residual expansion of concrete cores drilled from the wall was low, ranging from 0.005 to 0.011. A shotcreting

thickness of 50 to 70 mm was adopted to accommodate the reinforcement.

No cracking was observed until seven months after repair by HPFRCC. The crack widths then developed to not more than 0.05 and 0.12 mm at 10 and 24 months after repair, respectively. **Figure 16** shows the state of cracking 12 and 24 months after repair. Meshes of fine cracks were similarly observed. Cracking was harder to observe 24 months after repair compared to 12 months after, being obscured by dirt accumulated on the surface. On the other hand, cracking was visually observed on repair with normal repair mortar (Block 9) just one month after repair, with crack widths developing to 0.03, 0.2, and 0.3 mm at 3, 10, and 24 months after repair, respectively.

3.6 Surface repair of viaducts

Owing to its low air- and water-permeability due to small crack widths, HPFRCC surface repair is expected to retard carbonation of concrete structures. Surface protection with an organic paint type lining may be applied to railway viaducts, which require durability, for maintenance against carbonation. However, such lining is prone to early cracking due to the movement of cracks
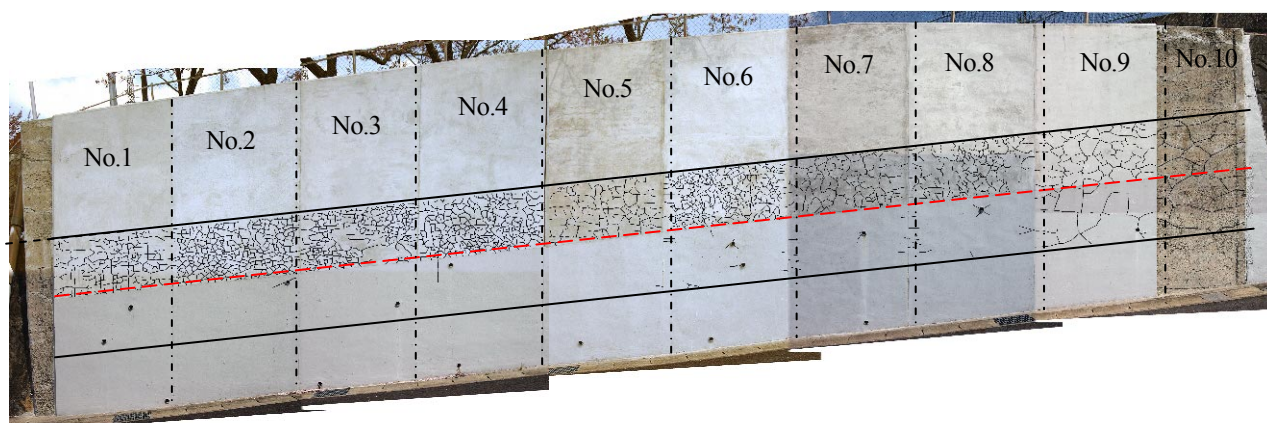
(a) 12 months
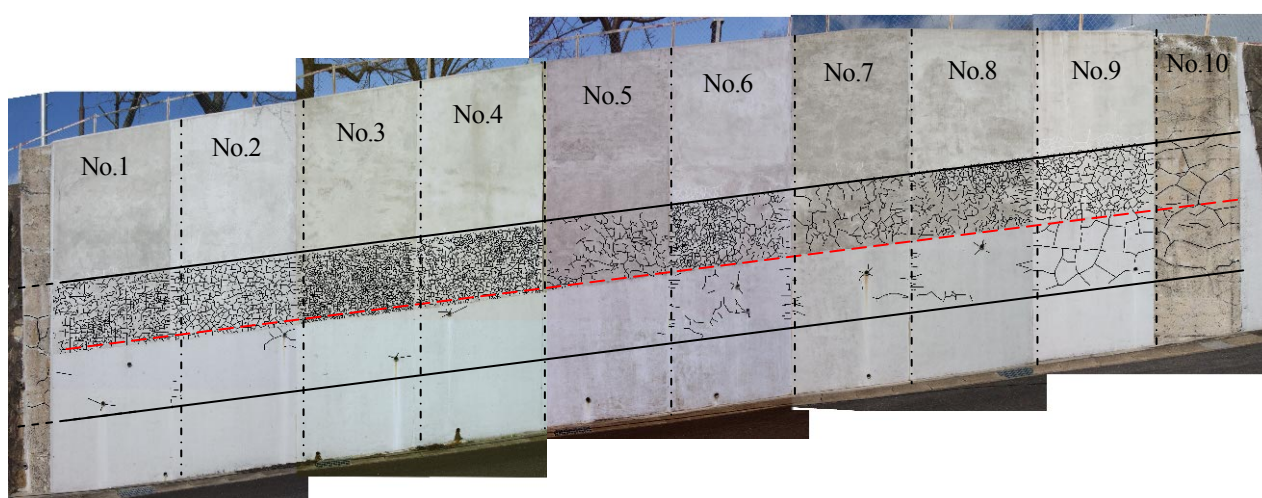
(b) 24 months

*Each numbers indicate a block number with different materials and reinforcements.

Fig. 16 Crack patterns at 12 and 24 months observation (Rokugo et al. 2005).

(opening and closing action) under the loads of railway traffic. Sprayed HPFRCC was applied to a thickness of 10 mm to viaduct girders having bending cracks for surface protection in 2005 (**Fig. 17**) (Suda and Rokugo 2005, Inaguma *et al.* 2005). Anchors were used to ensure bonding between the substrate concrete and HPFRCC.

Prior to the trial tests, alternate loading tests were conducted with small stress amplitudes to assume railway traffic loading on reinforced concrete beams having bending cracks, with HPFRCC sprayed onto the bottom surfaces. After alternate loading for 17 million cycles, the crack width of reinforced concrete beams with sprayed HPFRCC was 0.13 mm, half that of beams without HPFRCC (0.25 mm), clearly demonstrating the effect of HPFRCC. The carbonation-suppressing effect of HPFRCC sprayed onto existing concrete surfaces was also confirmed by accelerated carbonation testing.

4. Concluding remarks

This paper introduces recent applications using HPFRCC in Japan, examining required performance for HPFRCC. Various tasks including those listed below remain to be done to facilitate the application of HPFRCC to existing structures.

(1) Clarification of required performance and its criteria through investigation of existing structural levels

For instance, it is well know that the ductility of HPFRCC helps to reduce damage of structures. HPFRCC also provides higher spalling resistance. However, how much ductility is required for structures? Quantitative requirements such as the deformation capacity of HPFRCC should be determined, as a structural response level rather than a material and/or elemental response level. Trial tests as described in the previous

Fig. 17 Surface repair of railway viaduct.

sections may be useful for a discussion of the required performance of structures using HPFRCC and its criteria.

(2) Supply of large amounts of HPFRCC in situ
Only a few companies can supply HPFRCC in situ, using ready mixed concrete plants. Their number should be increased and most concrete-related institutes should define HPFRCC process technology in addition to establishing quality control methods.

(3) Proposal of prediction tools for performance of structures with HPFRCC
Predicting the performance of structures that use HPFRCC through numerical analysis is important. Not only mechanical performance (structural response) but also time dependent performance (durability) should be accurately simulated to determine the advantages of HPFRCC.

(4) Cost reduction
The material cost of HPFRCC is more expensive than that of ordinary concrete at this time. In addition to direct material cost reductions, maintenance taking into consideration life cycle cost should be promoted.

(5) Reduction of environmental impact
Ordinary construction materials can contribute to the reduction of environmental impact by using waste or recycled aggregate. The attainment of long life structures through the use of HPFRCC might contribute to sustainable development, and this concept should be simulated in existing structures. Strategies to reduce environmental impact such as recycling, use of waste, and rebuilding should also be prepared for HPFRCC structures.

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