Committee Report

DFRCC Terminology and Application Concepts

JCI-DFRCC Committee[1]

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Abstract

This paper is a summary report based on the discussions of the JCI-DFRCC committee. The paper attempts to summarize the terminology related to DFRCCs and the structural advantages and application concepts of DFRCCs. This attempt was made for the purpose of further discussion at the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites -Application and Evaluation- held in 2002 at Takayama, Japan.

1. Introduction

New materials make new promises using new terminology. To date, various composites have been developed towards specific targets, and those targets were often explained using specific terminology. DFRCCs (Ductile Fiber Reinforced Cementitious Composites) are no exception. DFRCCs boast significant differences from conventional cementitious materials such as concrete and fiber reinforced concrete. Hence, DFRCC terminology has been prepared to explain those differences and to construct innovative structural application concepts.

This paper is a summary report based on the discussion of JCI-DFRCC (JCI Committee on DFRCCs), and it attempts to summarize the terminology related to DFRCCs. In addition to covering terminology related to the material properties of DFRCC, this paper also provides a brief description of the structural advantages and application concepts of DFRCCs. This is because the establishment of links between material properties and structural applications is becoming important as DFRCC research enters the next stage.

This paper consists of three parts. First, DFRCC terminology is summarized with brief explanations. Next, various DFRCCs are introduced with a description of their features. Finally, the advantages and application concepts of DFRCCs are summarized based on past research papers.

2. DFRCC terminology

Ductile fiber reinforced cementitious composite, DFRCC:

DFRCC (Ductile Fiber Reinforced Cementitious Composite) is a class of FRCCs (ccFiber Reinforced Cementitious Composites) that exhibit multiple cracking (**Fig. 1** and **Table 1**). Multiple cracking leads to improvement in properties such as ductility, toughness, fracture energy, strain hardening, strain capacity, and deformation capacity under tension, compression, and bending. These improved properties of DFRCCs have triggered unique and versatile structural applications/concepts, including damage reduction, damage tolerance, energy absorption, crack distribution, deformation compatibility, and delamination resistance.

DFRCC is a broader class of materials than HPFRCC (High Performance Fiber Reinforced Composite) (**Fig. 1** and **Table 1**). HPFRCC is an FRCC that shows multiple cracking and strain hardening in tension, and therefore in bending as well (Naaman and Reinhardt 1996). On the other hand, DFRCC encompasses a group of FRCCs that exhibit multiple cracking in bending only, in addition to HPFRCCs. The focus on DFRCC is due to the need to generally explore the role of multiple cracking and the utilization of accompanying properties and structural applications/concepts in this broad class of materials. With their broad scope and basis on accumulated knowledge in the research community, DFRCC studies are expected to lead to the development and evaluation of new materials, the development of innovative structural applications/concepts, and the establishment of relations between structural applications/concepts and required material performance.

Fiber reinforced cementitious composite, FRCC:

FRCC includes the entire class of fiber reinforced cementitious composites. It includes DFRCC as well as other composites such as fiber reinforced concrete (FRC) and fiber reinforced mortar (FRM).

Strain hardening/pseudo strain hardening:

Strain hardening describes a phenomenon where, under uniaxial tension, transmitted tensile stress increases successively even after first cracking, with continued tensile straining. The term "pseudo strain hardening" is sometimes used instead, since the strain hardening mechanism of DFRCC is different from that of metallic materials (**Fig. 2** and **Table 1**). During strain harden-

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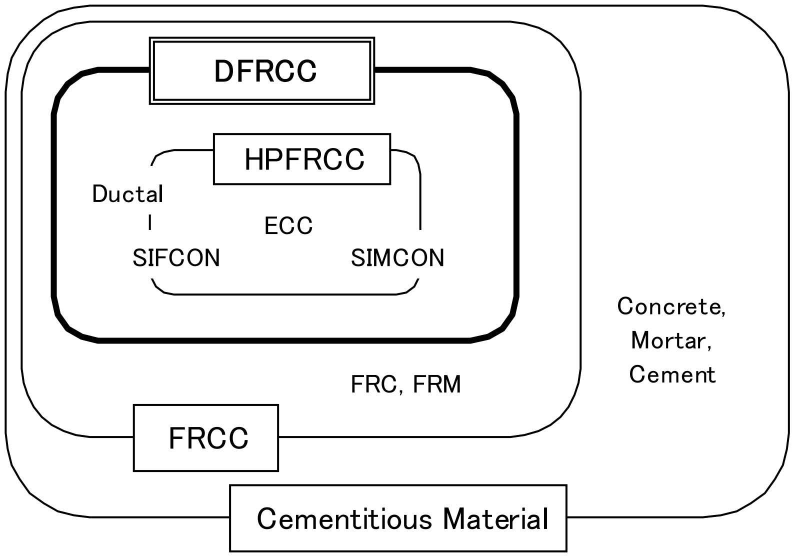

Fig. 1 Classification of cementitious materials.

ing/pseudo strain hardening, the stress-strain curve (**Fig. 2**) is uniquely defined and is a true material property. Strain hardening under flexure refers to the continuous rise in bending moment after a flexural crack has formed in the specimen, as the rotation angle increases.

Strain softening:

Strain softening describes a phenomenon that, under uniaxial tension, transmitted tensile stress decreases upon first cracking or after strain hardening (**Fig. 2** and **Table 1**). During strain softening, the "strain" is not uniquely defined, but depends on gauge length. Deformation at this stage is more appropriately described by crack opening displacement. Under flexure, strain softening refers to the decreasing moment as the rotation angle increases.

Multiple cracks / plural cracks:

Under uniaxial tension, cracks are successively formed even after first cracking, and finally those cracks become nearly equally spaced in parallel. When dense and fine multiple cracks are formed, a pseudo uniform deformation field is attained, and therefore deformation is often expressed in terms of strain instead of crack opening displacement.

Localized crack:

Under uniaxial tension, deformation localizes in the transition from uniform deformation field (elastic or multiple cracking deformation) to the crack opening displacement of a single crack.

Crack spacing, saturated multiple cracks:

Under uniaxial tension, the spacing between multiple cracks continues to decrease until saturation occurs. The crack spacing at saturation is a property of an HPFRCC composite.

Crack width:

In some HPFRCCs, the width of a crack reaches a cer-

Table 1 Characteristics of cementitious materials.

	Cement, Mortar	Concrete, FRC	**DFRCC**	
				HPFRCC
Material response	Brittle	Quasi brittle	**Quasi brittle (tension)-Ductile (flexure)**	**Ductile**
Strain softening/ hardening	-	Strain softening	**Strain softening (tension)-hardening (flexure)**	**Strain hardening**
Cracking behavior (flexure)*	Localized cracking	Localized cracking	**Multiple cracking**	**Multiple cracking**
Cracking behavior (tension)	Localized cracking	Localized cracking	**Localized cracking**	**Multiple cracking**

* : Cracking behavior in flexure is dependent on specimen dimensions. In this report, tested and analyzed specimens 100 x 100 x 400 mm.

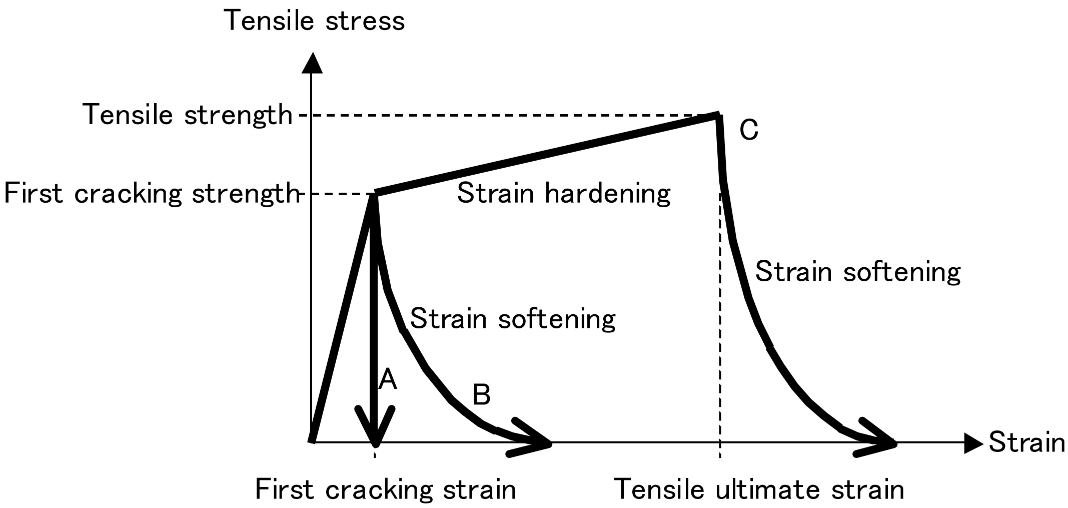

Fig. 2 Definition of A: brittle, B: quasi brittle, and C: ductile behavior as well as strain softening and strain hardening under uniaxial tensile loading.

tain level, but becomes constant as tensile strain continues to increase. This constant crack width is a property of the composite. In contrast, the crack width of other materials is dependent on steel reinforcement (amount, diameter and bond properties) in a structure.

Brittle, quasi brittle, ductile:

Under displacement-controlled uniaxial tension, fracture behavior upon first cracking are classified into three types: brittle, quasi brittle, and ductile. Brittle behavior is characterized with the complete loss of tensile stress upon first cracking and following a through crack formation. Quasi brittle behavior shows the gradual decay of tensile stress (strain softening) with or without slightly improved tensile strength beyond first cracking strength (strain hardening). Ductile behavior accompanies the gradual increase in tensile stress (strain hardening), before strain softening arises. These fracture behaviors are affected by specimen dimensions and loading conditions. Although fracture behavior generally tends to be brittle with larger specimen dimensions, an HPFRCC with inherent damage tolerance is ductile even under such conditions (**Fig. 2** and **Table 1**).

First cracking strength, first cracking strain, tensile strength, tensile ultimate strain, strain capacity:

Under uniaxial tension, first cracking strength is the stress level at which the first crack is formed, and first cracking strain is the corresponding strain. Tensile strength is the maximum stress attainable, and tensile ultimate strain or strain capacity is the corresponding strain. The tensile ultimate strain is a direct measure of material ductility. When tensile stress increases after first cracking (strain hardening), first cracking strength does not necessarily coincide with tensile strength. See **Fig. 2** and **Table 1**.

Tension toughness, compression toughness, flexure toughness:

Toughness describes energy absorption, which is given by the area below stress-strain curve or load-displacement curve either in tension, compression, or flexure. In practice, toughness is calculated based on the area up to a prescribed strain or displacement.

Bridging law, tension softening diagram/tension softening law:

Bridging law is the relation between stress transmitted across a crack and crack opening displacement. Stress is transmitted through aggregates and/or fibers, and, as a crack opens up, transmitted stress increases or decreases. The former is called hardening bridging law, the latter softening bridging law, tension softening diagram, or tension softening law. The bridging law is a fundamental material parameter that governs hardening/softening behavior in tension, compression, or flexure. However, the hardening/softening of the bridging law does not coincide with the overall hardening/softening behavior in either loading mode. On the scale of laboratory specimens or structural elements, the bridging law describes the traction-displacement at a point on a crack, which, in the case of a flexural specimen, has varying crack opening magnitude along the crack line. The bridging law is a composite material property averaged over an area of a representative volume of material with many fibers. In contrast, the behavior of a flexural specimen depends on its geometry and loading configuration and is therefore not a real material property, even though its behavior reflects the shape of the bridging law.

3. Various DFRCCs

The advantage of DFRCCs is increased toughness under tensile stress. Among a variety of DFRCCs, some

DFRCCs achieve pure tension toughness and ductility that are comparable to those of metallic materials, while others show increased toughness only under flexural tension. Descriptions of various DFRCCs reported in the literature are provided below.

ECC (Engineered Cementitious Composite) (Li 1993)

Engineered Cementitious Composite (ECC) is a special type of HPFRCC that has been microstructurally tailored based on micromechanics. ECC typically has a tensile strain capacity of more than 3%, with spacing between multiple cracks at saturation of less than 3 mm. Microstructure optimization allows ECC to be made with fiber content less than 2% to 3%.

SIFCON (Slurry Infiltrated Fiber CONcrete), SIMCON (Slurry Infiltrated Mat CONcrete) (Reinhardt and Fritz 1989)

SIFCON is produced by infiltrating slurry into pre-placed steel fibers in a formwork, and, due to the pre-placement of fibers, its fiber volume fraction can amount to 20% maximum. The confining effect of numerous fibers yields high compressive strength reaching 210 MPa, and the strong fiber bridging leads to tensile strain hardening behavior in some SIFCONs. SIMCON uses pre-placed fiber mat instead of steel fibers.

Ductal (Ductal Website 2002)

Ductal is an inorganic composite material based on the concept of RPC (Reactive Power Concrete). RPC utilizes reactive powder, and it is designed with optimal packing theory. Ductal is a cement based composite reinforced with steel fibers under the concept of high strength and high toughness. The properties of Ductal are characterized by high strength (210 MPa in compression and 45 MPa in flexure), high durability (100 in freeze-thaw durability factor), and high flowability (270 mm in flow value).

4. Advantages and application concepts of DFRCC

It is significantly important to establish the linkage between DFRCC properties and structural applications. To date, various advantages and application concepts have been proposed. These advantages and application concepts of DFRCC are summarized in

Table2. The material properties of DFRCC are given in terms of crack geometry and material response, and the resulting advantages and application concepts are shown for structural response and structural durability. Among these, unique advantages and application concepts are explained below. However, this does not mean that any DFRCC can realize these advantages and application concepts. Some of the advantages and concepts are realized and mechanically explained only with a specific DFRCC, and therefore it should be noted that they are described based on that specific DFRCC.

Role of multiple cracks and application of DFRCC:

The unique properties and structural applications of DFRCC are physically originated from the formation of multiple cracks. Multiple cracks play many roles, and the application of DFRCC in this regard is still being explored actively. Although the performance requirements of DFRCC will be clarified for various applications, roles could be tentatively distinguished for two cases: flexure and tension. This is because some DFRCCs do not show multiple cracks under tension, which is a more difficult material design condition than flexure. When multiple cracks take place under tensile stress, they also take place under flexural stress due to the more stable configuration of flexural cracks. Hence, if a DFRCC satisfies the second case, it naturally satisfies the first case as well. If it satisfies only the first case, only flexural application should be considered.

Role of fiber bridging in DFRCC:

Fiber bridging provides closing traction to a crack and transmits stresses across the crack. Due to relatively strong fiber bridging, DFRCC can expect to benefit from the multiple roles of fiber bridging. The following are a few notable examples. DFRCC exhibits smaller crack widths or delayed cracking at the same loading level. This is beneficial to activate the aggregate interlock on a crack, and reduction in shear modulus after cracking can be avoided. Another example is that DFRCC provides the transmission of stresses across a crack; thereby it shares the tensile stress with the steel reinforcement. This, for example, leads to the improved ultimate load capacity and ductility of a column member, as it shares stress with transverse reinforcement.

Damage reduction:

DFRCC in a structural/non-structural member can reduce member damage. For example, if the maximum shear crack width of a member after earthquake loading is below the critical value from the viewpoint of durability and serviceability, it is possible to secure durability and serviceability for the post-earthquake usage without making repairs or retrofitting (Fukuyama et al. 2000)

Damage tolerance:

Initial defects in a brittle material are an important factor influencing the safety of a structure, since such defects may lead to fast brittle fracture via gradual propagation. While unreinforced cementitious materials are a typical example of materials prone to brittle fracture, ECC shows an altogether different cracking behavior. In ECC, the propagation of an initial defect is shielded by the formation of a multiple cracking zone at the crack tip, and further multiple cracks are promoted at other locations. Therefore, ECC does not exhibit the dominant

Table 2 Application concepts in terms of material properties (in tension, partly in compression as well) and structural response/durability.

			Structural response	Structural durability
Material properties	Crack geometry	Small crack width	Damage reduction, Aggregate interlock activation	Infiltration control, Self-healing
		Multiple cracks	Non-localized steel yielding	Non-localized steel corrosion?
	Material response	High fracture toughness	Spall resistance, Kink-crack trapping (in case of rapid rise in R-curve) in repaired structures	Durable repair
		High strain capacity	Damage tolerance, Energy absorbing element, Steel-compatible deformation, Structural ductility, Possible use of FRP as reinforcement, Reduction or elimination of shear reinforcements	Minimize repair needs of structures after severe loading
		Strain hardening	Safety margin / fail-safe? Property robustness	
		High strength	Light structure, Stress sharing with steel	
		High fatigue strength		Long life structure under repeated mechanical loads

propagation of an initial defect, resulting in ductile fracture. Damage tolerance means higher tolerance for initial defects, which ECC realizes on the material level (Li et al. 2000). On the other hand, damage reduction means additional structural performance that DFRCC imparts effectively. Damage tolerance generally leads to damage reduction. However, damage reduction does not necessarily imply damage tolerance.

Energy absorbing element:

DFRCC can be applied to a plate member such as a wall. DFRCC works as an energy absorbing element, thus reducing the displacement response of the entire structure and the damage of other structural elements. This kind of element can absorb energy even with a small displacement, and thus it is suitable for stiff structures such as reinforced concrete structures (Fukuyama et al. 2000; Li et al. 2000).

Infiltration control, crack distribution, crack width suppression effect:

DFRCC can form fine and distributed multiple cracks under tension or flexure compared to concrete and FRC. This is advantageous since the infiltration of water soluble aggressive substances (which cause steel reinforcement corrosion in reinforced concrete structures) can be reduced, and therefore improved durability can be expected (Maalej and Li 1995).

Self-healing:

ECC forms fine multiple cracks densely under tensile stress. The advantage of ECC is that the width of these cracks can be controlled within tens of micrometers or less, so that it is possible to seal and reheal the cracks with the use of adhesive. Based on this concept, a passive type self-healing ECC has been developed and shown to be feasible (Li et al. 1998).

Steel-compatible deformation, deformation compatibility:

ECC deforms pseudo uniformly due to dense and fine multiple cracks; therefore it shows a deformation capacity comparable and compatible to that of steel. While conventional reinforced concrete members suffer from steel yielding at localized cracks, reinforced ECC members attain deformation compatibility and utilize the deformation capacity of steel to a greater extent, contributing to the improved deformation capacity of members (Fischer and Li 2002).

Kink-crack trapping, delamination resistance:
Unique cracking behavior is observed at the bimaterial interface between ECC and other cementitious materials. In general, either interfacial delamination or material fracture becomes dominant, when a structure made of two materials bonded together fails. This poses a serious dilemma for achieving durable bimaterial interface for repair or retrofit. However, this dilemma can be resolved with the use of ECC as a repair or retrofit material. Namely, unique cracking behavior can be achieved in a way that delamination at the bimaterial interface, crack kinking to ECC, kink-crack trapping in ECC, and again delamination at the bimaterial interface repeatedly take place. Hence, neither interfacial delamination nor material fracture dominates, and it is possible to construct a durable bimaterial interface for repair or retrofit (Lim and Li 1997).

5. Concluding remarks

This paper has summarized DFRCC terminology, introduced various DFRCCs, and described the advantages and application concepts of DFRCCs. Further discussion on the linkage between material properties and structural applications is expected for a new stage in DFRCC research.

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