TENSILE CHARACTERISTICS EVALUATION OF DFRCC - ROUND ROBIN TEST RESULTS BY JCI-TC -

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Abstract

Japan Concrete Institute (JCI) had organized Technical Committee (JCI-TC) on Ductile Fiber Reinforced Cementitious Composites (DFRCC) research from 2001 to 2004. The WG concerning with tensile performance of DFRCC had been organized in JCI-TC for the purpose of evaluating tensile characteristics and establishing standard test method for DFRCC. Four types of uniaxial tensile tests and bending test were carried out in order to compare the differences between testing method and to propose standard test method.

From the uniaxial tensile test results, it can be recognized that tensile characteristics differ by four types of test method and casting direction of DFRCC. Evaluating method for tensile strength and ultimate strain of DFRCC is proposed by using bending test results.

1. INTRODUCTION

Ductile Fiber Reinforced Cementitious Composites (DFRCC) are defined as "the cementitious composite material reinforced with short fiber, which show multiple cracking characteristics under bending stress, and whose ductility as bending, tension and compression failure are drastically improved." [1] These characteristics give a high potential in the improvement and development of multi-purpose performances of reinforced concrete structures. Japan Concrete Institute (JCI) had organized Technical Committee (JCI-TC) on DFRCC research from 2001 to 2004. At first term of this JCI-TC, the round robin test for DFRCC had been conducted in order to understand mechanical performance in wide range of DFRCCs, to evaluate DFRCCs performance using consistent standard, and to establish consistent testing methods to evaluate DFRCC performance. [2] In this round robin test, it had been mainly focused on the comparisons of DFRCC performance between several types of fiber and mixing design, and so on. Direct tensile test was conducted only for two types.

At the next term of JCI-TC, the WG concerning with tensile performance of DFRCC had been organized for the purpose of evaluating tensile characteristics and establishing standard test method for DFRCC. In this WG, direct tensile tests had also been conducted for several types of DFRCC. Four types of tensile tests were carried out in order to compare the differences between testing method.

In this paper, the results of the round robin test by JCI-TC are reported. Discussions are considered mainly for one type of DFRCC, i.e. PVA-ECC.

2. OUTLINE OF ROUND ROBIN TEST

2.1 Testing method

Four types of uniaxial tensile test, compression test and bending test were performed for the round robin test. These testing methods are summarized in Table 1 and tensile test methods are shown in Figure 1. Uniaxial tensile tests are named as T1, T2, T3 and T4. T1 specimen is plate type specimen with 30 x 13mm section. [3] This specimen is commonly used for tensile test of ECC. However, it is apprehensive to use plate type specimen for 2-

Table 1: Test method

Test method	ID	Casting direction	Shape of specimen	Loading condition
Uniaxial tensile	T1	Horizontal	30 x 13mm Plate	Pin-Fix
	T2-H	Horizontal	100 x 60mm Dogbone	Pin-Fix
	T2-V	Vertical		
	T3	Vertical	ϕ 70mm Dogbone	Pin-Fix
	T4	Vertical	ϕ 100mm Cylinder	Fix-Fix
Compression	C	Vertical	ϕ 100mm Cylinder	Fix-Fix
Bending	B-H	Horizontal	100 x 100 x 400mm Rectangle	Four point bending
	B-V	Vertical		

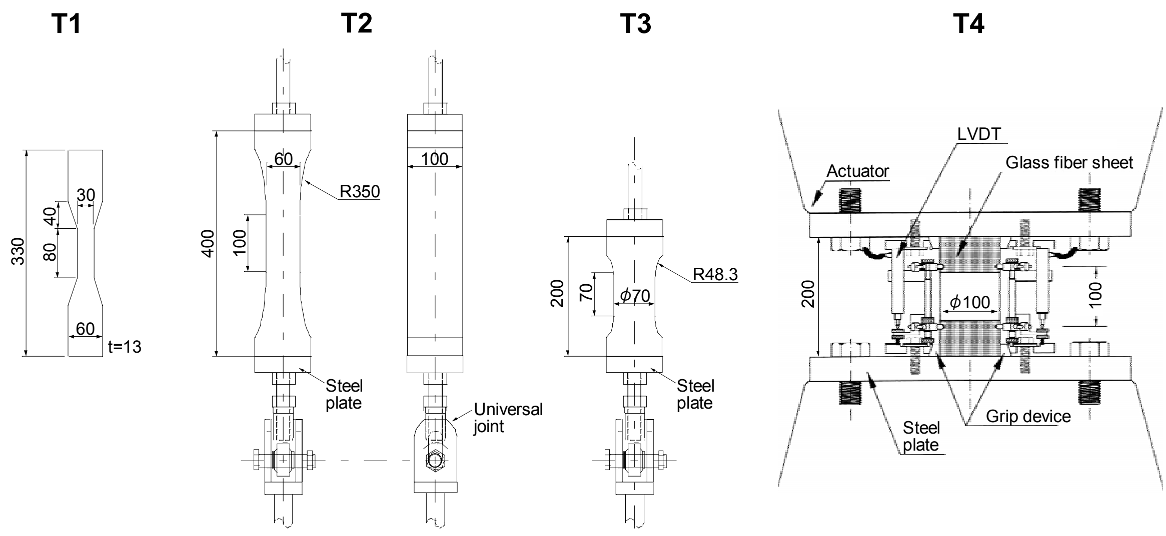

Figure 1: Uniaxial tensile test method

dimensional fiber orientation considering structural application in actual elements. Specimens T2, T3 and T4 have been developed to improve the effect of fiber orientation with large size of section, in which fiber has 3-dimensional orientation. Specimen T2 has rectangle section with 100 x 60mm size, which are made using 100 x 100 x 400mm mold with curved plates as shown in Figure 2. [4] Specimen T3 has 70mm circular section, which are shaped utilized cylinder mold as shown in Figure 3. [5] For Specimen T4 and compression test, ordinary cylinder specimen was utilized. [6]

It is considered that fiber orientation is influenced by casting direction. [7] For specimen T2 and bending test specimen, DFRCC was compacted by horizontal and vertical casting direction.

Support conditions are one of the important factors to conduct direct tensile test for cementitious materials. In actual loading, it is impossible to perform "pure tension" because of un-uniformity of material itself and scattering of specimen shape and setup. Pin-fix ends support condition was selected for T1, T2 and T3 loading to decrease the effect of eccentricity moment of tensile load and secondary moment after cracking.

The bending test was carried out by four-point loading with same spans of 100mm. LVDTs were set on both sides of specimen in order to measure deflection and curvature at pure bending section as shown in Figure 4.

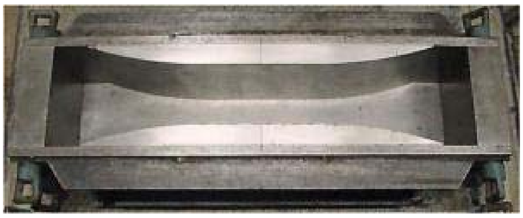

Figure 2: Mold for T2-H tensile test

Figure 3: Mold for T3 tensile test

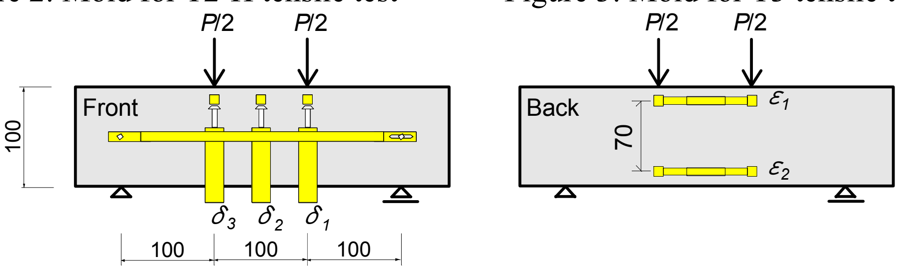

Figure 4: Bending test method

Table 2: Testing DFRCC

DFRCC	Water / binder ratio	Fiber type	Fiber volume content	Fiber characteristic			
				Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
PVA-ECC	46%	PVA	1.9%	12	0.04	1600	40
PE-ECC	30%	PE	1.5%	12	0.012	2600	73
HB*1	45%	PE	1.0%	15	0.012	2600	73
		Steel	1.0%	32	0.405	2700	200
DCT*2	22%	Steel	2.0%	15	0.2	2500	210

*1 : Hybrid DFRCC involving both PE and steel fiber *2 : Reactive powder composite

2.2 Testing DFRCC

Four types of DFRCC were tested. Used fiber for each type of DFRCC is listed in Table 2. In this paper, the test results are discussed mainly for PVA-ECC.

3. TEST RESULTS

3.1 Compression test result

Compression test results for PVA-ECC are summarized in Table 3. Coefficient of variation of compressive strength is around 10%.

Table 3: Compression test results (PVA-ECC)

Number of specimen = 9	Compressive strength	Compressive strain at maximum	1/3 Secant modulus
Average	35.7 MPa	0.45 %	15.8 GPa
COV	10.3 %	18.1 %	10.9 %

3.2 Uniaxial tensile test result

Uniaxial tensile test results for PVA-ECC are summarized in Table 4. Although number of specimens for each type of test method is not the same, it can be recognized that tensile characteristics differ by four types of test method and casting direction. As expected, tensile strength and tensile strain at maximum load obtained from T1 specimens shows highest level rather than other test method. Comparing the casting direction, specimen T2-H has higher strength and strain than specimen T2-V. Specimen T4 shows lowest crack and maximum strength. Coefficient of variation for tensile strength ranges from 4% to 15%, which are almost same values with the case of compression test. Coefficient of variation for strain indicates around 30%, which is scattered rather than compression test results.

Tensile stress and tensile strain relationships are shown in Figure 5. In T3 test method, strain hardening behavior can not be observed.

Table 4: Uniaxial tensile test results (PVA-ECC)

Test method (Number of specimen)	At first crack				At maximum load			
	Tensile stress		Tensile strain		Tensile stress		Tensile strain	
	Average (MPa)	COV (%)	Average (%)	COV (%)	Average (MPa)	COV (%)	Average (%)	COV (%)
T1 (10)	3.66	26.9	0.021	23.6	4.95	9.3	2.26	37.9
T2-H (5)	2.29	9.6	0.015	13.6	4.10	3.7	1.89	29.7
T2-V (1)	2.51	-	0.016	-	2.87	-	0.77	-
T3 (3)	4.26	14.5	0.023	22.5	4.26	14.5	0.023	22.5
T4 (3)	1.54	32.4	0.051	56.7	1.78	12.2	0.32	73.9

3.3 Bending test result

Bending test results for PVA-ECC are summarized in Table 5. Bending moment and curvature at maximum load obtained from B-H specimens are bigger than those from B-V specimens. This tendency shows same result with tensile test concerning with casting direction. Bending moment and curvature relationships are shown in Figure 6. "Deflection hardening" behavior can be observed in the all tested specimens.

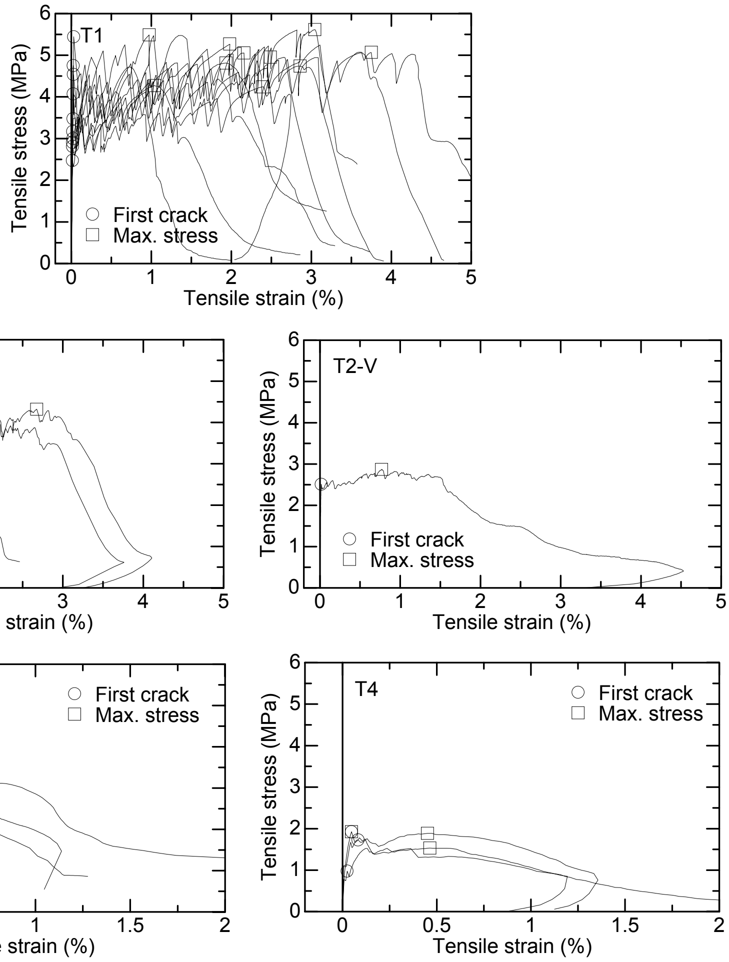

Figure 5: Tensile stress – strain relationships (PVA-ECC)

Table 5: Bending test results (PVA-ECC)

Test method (Number of specimen)	At first crack				At maximum load			
	Bending moment		Curvature		Bending moment		Curvature	
	Average (kN・m)	COV (%)	Average (10^{-6}/mm)	COV (%)	Average (kN・m)	COV (%)	Average (10^{-6}/mm)	COV (%)
B-H (9)	0.59	24.9	4.5	23.4	1.88	14.8	237.4	43.9
B-V (9)	0.45	22.7	3.5	48.6	1.18	18.8	101.9	86.6

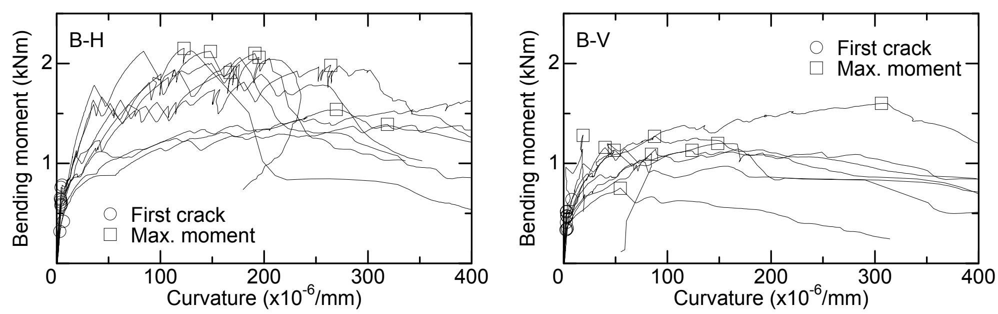

Figure 6: Bending moment – curvature relationships (PVA-ECC)

4. PROPOSAL OF TENSILE CHARACTERISTIC EVALUATION METHOD

4.1 Section analysis

Simple section analysis is proposed to clarify correlation between tensile and flexural behavior in PVA-ECC. ECC's flexural behavior can be represented by moment – curvature relation, which is directly connected to compressive and tensile stress – strain relation via this section analysis. Similar approach has been proposed for ECC flexural behavior investigation in literature [8], where knowing stress – strain relation in compression and tension successfully reproduced ECC's moment – curvature profile. It should be noted that this connection occurs due to ECC's ductile behavior. Contrary to ECC, flexural behavior of brittle or quasi-brittle materials, in which most of existing cementitious materials are incorporated, are not reproduced via this stress – strain based section analysis. For quasi-brittle material, different type of section analysis including tension softening relation of material is required to reproduce flexural behavior. [9]

The constitutive laws are defined for the section analysis as shown in Figure 7 taking into account the results of compression test and uniaxial tensile test. Perfect elastic – plastic model is selected to represent tensile stress – strain curve. Parabola model is chosen for compressive stress – strain relation. An example of moment – curvature relationship obtained by section analysis is shown in Figure 8. The points I and III indicate first cracking and maximum moment point, respectively. Stress distributions that correspond to points I to IV are also shown in Figure 8. In the point I, tensile stress at the tension edge is equal to maximum stress in perfect elastic – plastic model. At the maximum moment point, tensile strain at the tension edge just becomes equal value to ultimate strain in perfect elastic – plastic model. Compressive stress at the compression edge is smaller than compressive strength, therefore compressive stress distributes almost lineally.

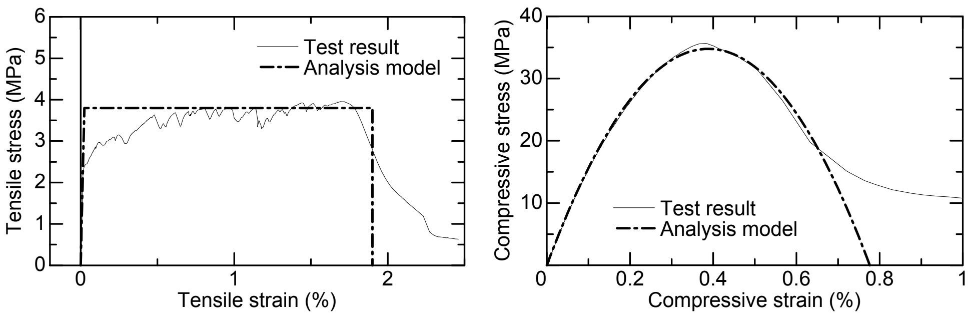

Figure 7: Stress – strain model for section analysis

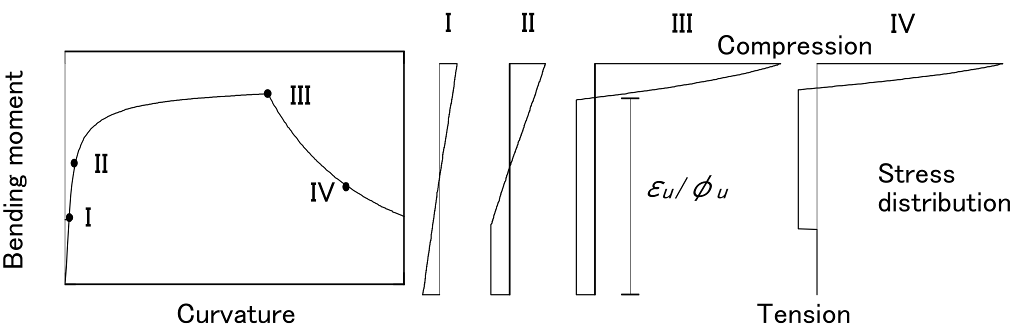

Figure 8: Stress distribution obtained by section analysis

4.2 Tensile characteristics identified by bending test results

The prescribed section analysis is utilized to identify tensile characteristics using bending test results. Identified parameters are: ultimate tensile strain, $\varepsilon_{u,b}$, and tensile strength, $\sigma_{t,b}$. Fitted data are maximum moment and curvature obtained by bending test. In deriving analytical formula for this identification problem, sectional tensile stress distribution at the maximum moment is simplified as rectangular shape, and compressive stress distribution is assumed linear as shown in Figure 9.

From the equilibrium of force and moment, Eq.(1) and (2) can be obtained.

$$\frac{E \cdot \phi_u \cdot b}{2} x_n^{\ 2} = \sigma_{t,b} \cdot (D - x_n) \cdot b \qquad (1)$$

$$M_{\max} = \frac{E \cdot \phi_u \cdot b}{3} x_n^{\ 3} + \frac{\sigma_{t,b} \cdot b}{2} (D - x_n)^2 \qquad (2)$$

where,

E : elastic modulus

ϕ_u : curvature at the maximum moment

x_n : neutral axis distance from compressive edge

$\sigma_{t,b}$: tensile strength

b : width of member

D : depth of member

M_{max} : maximum moment

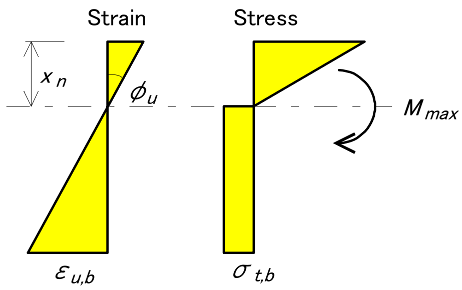

Figure 9: Stress distribution assumption

From the Eq.(1) and (2), m_{max}, which is M_{max} / bD^2, can be expressed by Eq.(3)

$$m_{\max} \equiv \frac{M_{\max}}{bD^2} = \frac{E \cdot \phi_u \cdot D}{3} x_{n1}^{\ 3} + \frac{E \cdot \phi_u \cdot D}{4} x_{n1}^{\ 2} (1 - x_{n1}) \qquad (3)$$

where, $x_{n1} = x_n / D$

Dividing Eq.(3) by $E \cdot \phi_u \cdot D$, m^*, which is newly introduced, is given by Eq.(4)

$$m^* \equiv \frac{m_{\max}}{E \cdot \phi_u \cdot D} = \frac{x_{n1}^{\ 3}}{3} + \frac{x_{n1}^{\ 2}(1 - x_{n1})}{4} \qquad (4)$$

Therefore, Eq.(5) can be obtained.

$$x_{n1}^{\ 3} + 3x_{n1}^{\ 2} - 12m^* = 0 \qquad (5)$$

Getting the value of x_{n1} leads $\varepsilon_{u,b}$ and $\sigma_{t,b}$ as shown in following equations.

$$\varepsilon_{u,b} = \phi_u \cdot D \cdot (1 - x_{n1}) \qquad (6)$$

$$\sigma_{t,b} = \frac{E \cdot \phi_u \cdot D \cdot x_{n1}^{\ 2}}{2 \cdot (1 - x_{n1})} \qquad (7)$$

Table 6 lists the identifying results according to the above equations. Calculated ultimate strain and maximum tensile stress show good agreement with tensile test results. This result implies that the proposed identifying procedure using bending test data is feasible for simple tensile property clarification.

Table 6: Comparison between uniaxial tensile test and bending test results

Specimen	Tensile stress (MPa)		Tensile strain (%)	
	Tensile test	Bending test	Tensile test	Bending test
T2-H vs B-H	4.10	4.22	1.89	2.05
T2-V vs B-V	2.87	2.79	0.77	0.86

5. CONCLUSIONS

- From the uniaxial tensile test results, it can be recognized that tensile characteristics differ by four types of test method and casting direction of DFRCC.
- Considering simple assumption of stress distribution in maximum bending moment condition, evaluating method of tensile strength and ultimate strain from bending test results is proposed.
- For PVA-ECC, the tensile strength and ultimate strain calculated by the proposed method show good agreement with tensile test results.

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