Invited paper

Tensile Characteristics Evaluation Method for Ductile Fiber-Reinforced Cementitious Composites

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Abstract

This paper presents a brief overview of the tensile test methods for concrete and cementitious composites. Comparisons of uniaxial tension test results for a round robin test conducted as part of a project of the Japan Concrete Institute Technical Committee (JCI-TC) for Ductile Fiber-Reinforced Cementitious Composites (DFRCC) are introduced. Four types of tensile test methods for four types of DFRCC were used in this round robin test. The results differ according to the testing method and compacting direction of DFRCC. The relationships between the tensile test results and tensile characteristics calculated from bending test results are discussed.

The possibility of establishing a standard test method for the evaluation of the tensile characteristics of DFRCC has been discussed by the Japan Concrete Institute Standard Committee. This discussion was based on the report of the JCI-TC and the results of the round robin test. Items that were discussed in further detail were (a) difficulties of uniaxial tension test as a standard test method, (b) treatment of DFRCC that does not have a strain hardening branch in tension, (c) adaptability of strain-based evaluation for cracked materials, and (d) relationship between uniaxial tensile characteristics and bending characteristics. The Standard Committee proposed the standard test method using the 4-point bending test to obtain bending moment–curvature curves. An evaluation method for the tensile strength and ultimate strain of DFRCC was added as an appendix of non-mandatory information. This method is considered to be one of the evaluation methods for the tensile characteristics of DFRCC.

1. Introduction

Ductile Fiber-Reinforced Cementitious Composites (DFRCC) are defined as cementitious composite material reinforced with fiber, which show multiple cracking characteristics under bending stress and feature drastically improved ductility during bending, tension and compression failures (JCI-DFRCC Committee 2003). High Performance Fiber-Reinforced Cementitious Composites (HPFRCC), which show a strain hardening branch and multiple cracking under uniaxial tensile stress, are included in DFRCC. It is important to evaluate and express the characteristics of DFRCC with suitable methods to enable the use of DFRCC for actual applications taking advantages of the merits of these composite materials.

Table 1 lists examples of DFRCC use in actual applications and the required characteristics. In the future, additional applications will emerge. At present, however, DFRCC use is largely confined to Japan. The slab strengthening method is an example of the effective application of the tensile characteristics of DFRCC. This method requires not only tensile strength but also tensile deformation capacity. On the other hand, tensile capacity is not directly required in the surface protection method. In this case, multiple cracking behavior featuring for

example cracks with a width of less than 0.1 mm is more important. It is a well-known that the multiple cracking behavior is the result of high tensile performance. However, very small crack widths are only required in actual situations. In the area of seismic strengthening, it is still not clear which performance characteristics of DFRCC are really required for the realization of high performance strengthening members. It is a fact that the high tensile strength and tensile deformation capacity of DFRCC produce ductile members. However, the confinement effect for the core of members is also important, and non-falling of the cover concrete leads good performance of members. Moreover, the tensile deformation capacity of DFRCC is not such an important factor for the shear performance of members. **Fig. 1** shows a comparison of beam shear test results under anti-symmetrical bending moment loading. Mortar without fiber (Shimizu *et al*. 2005), ultra high strength concrete (UFC: Ductal[TM]) (Ujiie *et al*. 2005) and PVA-ECC (Shimizu *et al*. 2005) are used for the upper, middle and lower specimens, respectively. The amount of main bar and stirrup ratio are the same for the three specimens. PVA-ECC with 2.0% volume percentage of fiber has almost 2% strain deformation capacity and multiple cracking behavior under uniaxial tensile stress. UFC has a very small strain hardening branch with a single crack. The crack behavior of beam specimens does not differ greatly between UFC and PVA-ECC specimens. Since UFC has compressive strength almost five times that of PVA-ECC, the maximum shear strength of

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the UFC specimen is 1.7 times that of the PVA-ECC specimen.

Demands for DFRCC vary according to the type of application. Thus, the evaluation method must be changed to match the application. In other words, evaluation of the tensile characteristic of DFRCC without considering its intended use is meaningless. The main point is how to best use DFRCC making the most of their merits.

This paper reports the results of comparisons of direct tensile test results for a round robin test conducted for DFRCC. This round robin test was conducted as part of a project of the Japan Concrete Institute Technical Committee for DFRCC (chaired by Prof. Rokugo of Gifu University). Following the completion of that project, JCI worked to standardize the evaluation method for the tensile properties of DFRCC. In the end, only the loading method using the 4-point bending test was established as the standard test method. The evaluation method for the tensile characteristics of DFRCC has been added as an appendix of the standard. The standard test method and the evaluation method are introduced in this issue of the Journal of Advanced Concrete Technology.

2. Tensile test for concrete and cementitious composite

This chapter provides a brief overview of the tensile test and bending test methods and evaluation methods for concrete and cementitious composites. Information about these tests and evaluation methods is helpful for understanding test and evaluation methods for DFRCC. In the case of ordinary concrete, tensile characteristics are not important in the design procedures of concrete structures and thus standardization of tensile test and evaluation methods is not a necessity. Furthermore, it is difficult to perform uniaxial tension tests because such tests require special molds and loading jigs. Usually, a splitting test and 3-point bending test are carried out instead of a uniaxial tension test.

2.1 Uniaxial tension test
The uniaxial tension test requires special devices for loading. **Fig. 2** shows some examples of end shapes of uniaxial tension test specimens (Kasai and Ikeda 1993). The main points here are the load transmitting mecha-
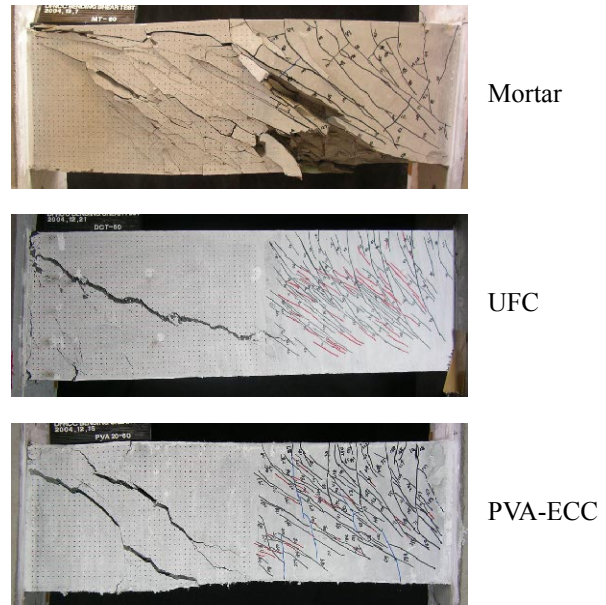

Mortar

UFC

PVA-ECC

Fig. 1 Comparison of shear test results for beam

nism (stress concentration) and boundary condition (moment transmission).

Failure at the end of a specimen or grip portion is observed in the case of specimens with a uniform cross section. It is also difficult to establish the gage length for measuring deformation (crack width). In the case of specimens with a large cross section at the specimen ends, failure occurs at the point where the cross sectional size varies because of stress concentration. The same phenomenon is observed when anchors are set into the specimens ends. Anchors should be shaped with sharp tips to reduce the stress concentration effect.

Three conditions, pin-pin, pin-fix, and fix-fix, can be considered as the boundary conditions. "Uniaxial tensile stress" may be considered as the ideal. Non-uniformity of material itself, the precision of specimen shapes, stiffness of the loading machine, setup conditions of specimens, etc., all contribute to bending moment occurrence. The pin-pin condition reduces the bending moment effect. However, cracking occurs from one side of specimens, and secondary moment is produced after cracking. The bending moment effect causes large errors in strength evaluation.

Table 1 Examples of actual applications and demands for DFRCC.

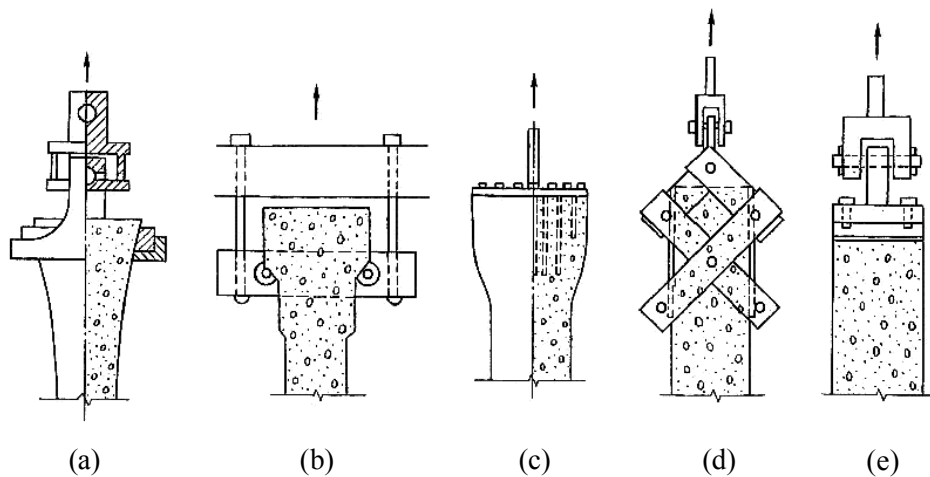| Application	Method	Demands
Slab strengthening	Spray up	Tensile capacity, Fatigue resistance, ・・・
Surface protection	PCa, Cast in situ, Spray up	Decrement of crack width, Reduction of penetration, ・・・
Seismic strengthening	PCa, Cast in situ	Strength capacity, Confinement for axial load, ・・・

<p align="center">(a)　　(b)　　(c)　　(d)　　(e)</p>

Fig. 2 Examples of end shapes for direct tensile test (Kasai and Ikeda, 1993).

Akita *et al.* have introduced an interesting uniaxial tension test method in which bending moment is applied to the specimens in order to eliminate the secondary moment by controlled DC motors to obtain a uniaxial tensile field. (Akita *et al.* 2005) This means that controlled bending moment is essential to realize uniaxial tension.

In general, there are scale effects in element tests. Smaller specimens, not only cementitious composites but also common materials, show higher strength. Especially in the case of concrete, the size of defects such as air voids, drying shrinkage and material segregation, is considered to affect strength. Furthermore, the ratio of fiber length to specimen dimensions and compacting direction has an influence in the case of fiber-reinforced concrete.

2.2 Splitting tensile test

A splitting tensile test is generally carried out to obtain the tensile strength of concrete. The stress field in the splitting tensile test is actually a biaxial stress field with compressive stress three times greater than tensile stress. From the previous study results, the tensile strength obtained by the splitting tensile test is in good agreement with the results obtained by the uniaxial tension test.

In the case of fiber-reinforced cementitious composites, specimens after first cracking do not separate unlike in the case of concrete failure. After fast cracking, a specimen is subjected to compressive loading, and tensile strength cannot be observed. Previous studies have reported setting strain gages or LVDTs at the end surface of the specimen and obtaining first cracking strength from the point at which displacement in the tensile direction increases remarkably.

2.3 Bending test

A modulus of rupture obtained by a bending test is generally used for concrete materials because of the easiness of making specimens and loading. However, the modulus of rupture is considered not to represent material char-

acteristics. Because the bending test is one of the structural tests, some considerations such as assumptions of strain and stress distribution are necessary in order to have relationships between structural characteristics and material ones.

It is difficult to measure deformation across a crack in the case of 4-point bending test. Therefore, the 3-point bending test is conducted for notched specimens in order to obtain the fracture energy or softening curve of the concrete. The Japan Concrete Institute and the Japan Society for Civil Engineers have already established a standard test method using a bending test to evaluate the fracture toughness of fiber-reinforced concrete.

The scale effect, drying shrinkage and material segregation all affect bending characteristics as in the case of the uniaxial tension test. Furthermore, slope of the strain distribution causes large difference between the modulus of rupture and tensile strength because of a reduction of softening curve contribution. Especially in the case of fiber-reinforced concrete, which has large fracture energy in the softening branch, slope of the strain distribution has a large effect on bending characteristics.

2.4 Affecting factor in tensile characteristics evaluation

In the case of concrete, a uniaxial compression test is commonly carried out to evaluate concrete characteristics. However, the results obtained by the compression test may differ depending on the specimen dimensions, shape, boundary condition, and so on. It may be considered that smaller load in the case of tensile test than compression test causes larger effect on those factors. Especially for the case of fiber-reinforced cementitious composites, fiber orientation and fiber length defined by relative scale to specimen size (2-dimensional or 3-dimensional orientation) has an effect on the characteristics of cementitious composites. The affecting factors in testing of cementitious composites are listed in **Table 2**.

The important points for these affecting factors are to

Table 2 Affecting factors in material testing.

Method	Affecting factor		Target	Effect
Compression test	Dimensions of specimen	Large	Compressive strength	Smaller
		Small	Elastic modulus	Larger
	Specific surface area of specimen	Large	Compressive strength	Smaller
		Small	Elastic modulus	Larger
	Length of test region	Long	Compressive strength Elastic modulus	Smaller
		Short	Ultimate strain	Larger
	End condition (Capping)	Hard	Compressive strength	Larger
		Soft	Elastic modulus	Smaller
	Stiffness of loading machine	Large	Softening curve	Measurable
		Small		Not measurable
	Boundary condition	Fix	Softening curve	Measurable
		Pin		Not measurable
Tensile test	Dimensions of specimens	Large	Tensile strength	Smaller
		Small	Tensile strain	Larger
	Specific surface area of specimen	Large	Tensile strength	Smaller
		Small	Tensile strain	Larger
	Length of test region	Long	Tensile strength	Smaller
		Short	Tensile strain	Larger
	End shape	Straight	Tensile strength Tensile strain	Stress concentration
		Other	Multiple crack	
	Boundary condition	Fix	Tensile strength Tensile strain	Smaller Measurable
		Pin	Multiple crack	Larger Not measurable
	DFRCC	Ratio of fiber length to specimen dimension	Large	Tensile strength Tensile strain	Larger
			Small		Smaller
		Casting direction (Fiber orientation)	Vertical	Tensile strength Tensile strain	Depend on DFRCC
			Horizon	Multiple crack	

know their existence and the possibility of relative evaluation. The accumulation of additional data through further research is strongly hoped for.

3. Round robin test for DFRCC

The Japan Concrete Institute established a Technical Committee (JCI-TC) on DFRCC research that operated from 2001 to 2004. In the first term of the JCI-TC, the round robin testing for DFRCC was conducted in order to understand mechanical performance in a wide range of DFRCCs, to evaluate DFRCC performance using consistent standards, and to establish consistent testing methods to evaluate DFRCC performance (Matsuo and Kanda 2002). The main focus of this round robin testing was the comparison of DFRCC performance for several types of fiber, mixing design, and so on. Uniaxial tension tests were conducted only for two types.

In the following term of JCI-TC activities, a WG on the tensile performance of DFRCC was organized for the purpose of evaluating tensile characteristics and establishing a standard test method for DFRCC. Uniaxial

tension tests for several types of DFRCC were also executed by this WG. Four types of tensile tests were carried out in order to compare differences among testing methods.

3.1 Outline of round robin test
3.1.1 Testing method

Four types of uniaxial tension test, compression test and bending test were performed for the round robin test. These testing methods are summarized in **Table 3** and the tensile test methods are shown in **Fig. 3**. The uniaxial tension tests are named T1, T2, T3 and T4. The T1 specimen is plate type specimen with a 30 x 13 mm cross section (Kanda and Li 1999). This specimen is commonly used for the tensile test of ECC. However, it is anxiety to use plate type specimen with 2-dimensional fiber orientation considering structural application in actual elements in which fiber orientation shows 3-dimension. Specimens T2, T3 and T4 have been developed to improve the effect of fiber orientation with large sectional size of specimens, in which the fiber has 3-dimensional orientation. Specimen T2 is a rectangle

Table 3 Test method of round robin test.

Test method	ID	Casting direction	Shape of specimen	Loading condition
Uniaxial tension	T1	Horizontal	30 x 13 mm plate	Pin-Fix
	T2-H	Horizontal	100 x 60 mm dogbone	Pin-Fix
	T2-V	Vertical		
	T3	Vertical	ϕ 70 mm dogbone	Pin-Fix
	T4	Vertical	ϕ 100 mm cylinder	Fix-Fix
Compression	C	Vertical	ϕ 100 mm cylinder	Fix-Fix
Bending	B-H	Horizontal	100 x 100 x 400 mm Rectangle	Four-point bending
	B-V	Vertical		
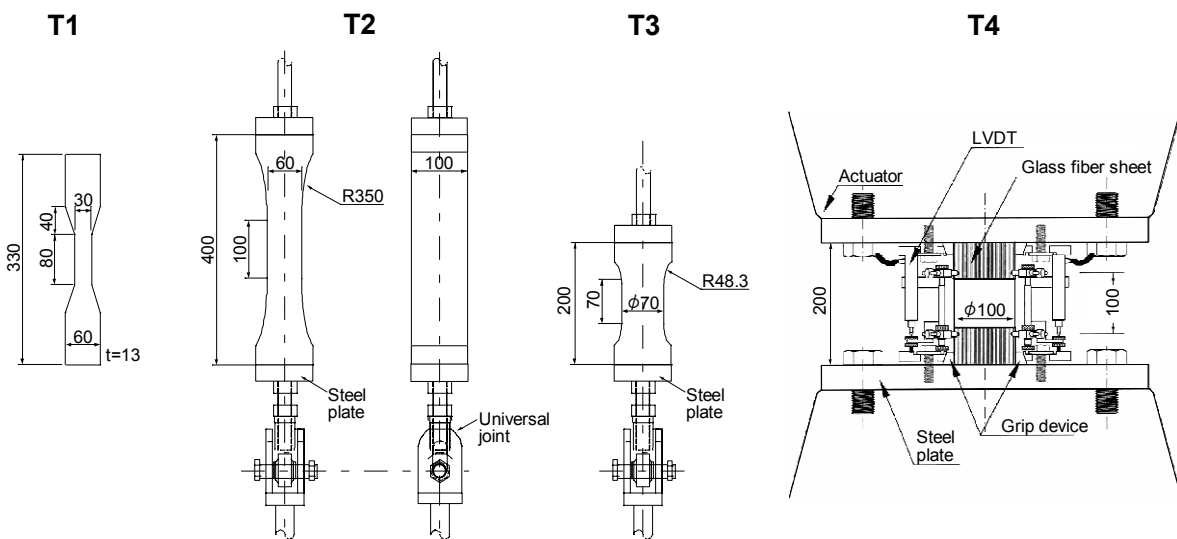
Fig. 3 Uniaxial tensile test method of round robin test.

Fig. 4 Mold for T2-H tensile test.

Fig. 5 Mold for T3 tensile test.

section measuring 100 x 60 mm, which is made using a 100 x 100 x 400 mm mold with curved plates as shown in **Fig. 4** (Shimizu *et al*. 2004). Specimen T3 has a 70 mm circular section, which is shaped using a cylinder mold as shown in **Fig. 5** (Furuta *et al*. 2003). For Specimen T4 and the compression test, ordinary cylinder specimens were used (Sato *et al*. 2001). For specimen T2 and the bending test specimen, DFRCC was compacted in the horizontal and vertical casting direction.

Support conditions are one of the important factors for conducting uniaxial tension tests for cementitious materials. In actual loading, it is impossible to perform "pure tension" because of the non-uniformity of the material itself and variations in specimen shapes and setup con-

ditions. The "pin-fix" ends 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 4-point loading using spans of 100 mm. LVDTs were set on both sides of the specimen in order to measure deflection and curvature at the pure bending section as shown in **Fig. 6**.

3.1.2 Testing DFRCC
Four types of DFRCC were tested. Used fiber for each type of DFRCC is listed in **Table 4**. A steel mold was used for specimens T1, T2-H and B-H. A tin mold was used for specimens T3, T4 and C. A composite wooden panel was used for the molds for T2-V and B-V. In principle, the number of specimens was three for each
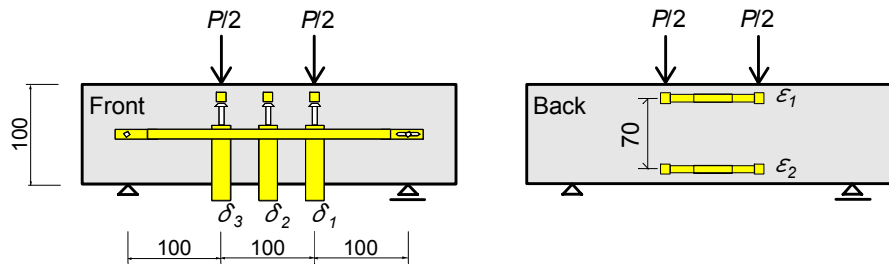
Fig. 6 Bending test method.

Table 4 Testing DFRCC for round robin test.

DFRCC	Water / binder ratio	Fiber type	Fiber volume content	Fiber characteristic			
				Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
PVA	46%	PVA	1.9%	12	0.04	1600	40
PE	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: UFC (Ductal[TM])

Table 5 Compression test results.

DFRCC	Unit weight (kg/m³)	Compressive strength			Strain at strength			1/3 secant modulus		
		Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)	Average (GPa)	SD (GPa)	COV (%)
PVA	1,788	31.3	0.8	2.7	0.555	0.045	8.0	13.7	0.1	1.1
PE	1,958	67.3	1.8	2.7	0.463	0.027	5.8	21.0	0.5	2.5
HB	1,997	43.6	2.7	6.3	0.442	0.065	14.6	17.4	1.2	7.0
DCT	2,490	198.0	3.7	1.9	0.430	0.005	1.2	52.8	0.9	1.8

DFRCC and specimen type. In the case of some tensile test specimens, the number was 5 or 6. When the mixer capacity was insufficient for making all the specimens, the same batch of DFRCC was dispersed to each type of specimens.

3.2 Test results
3.2.1 Compression test result
The compression test results are summarized in **Table 5**. The coefficient of variation (COV) of compressive strength ranges from 2 to 6%.

3.2.2 Uniaxial tension test result
The uniaxial tension test results of T1 are summarized in **Table 6**. **Figure 7** shows the tensile stress–tensile strain curves. The tensile strain was obtained by displacement measured by LVDTs divided by gage length.

The T2 tensile test results and tensile stress–tensile strain curves are shown in **Table 7** and **Fig. 8**, respectively. The tensile strain is calculated from the displacement measured by LVDTs. Although loading was carried out for three specimens for each type of DFRCC, one or two of these specimens failed outside the contact points of LVDT. In the case of the DCT specimens, loading could not be completed for any of the specimens

because of delamination of the steel plates.

Some differences between horizontal compacting (T2-H) and vertical compacting (T2-V) specimens are recognized. However, this tendency differs according to the DFRCC type, i.e., T2-H specimens show larger strength and strain than T2-V specimens in the case of PVA and HB, and the opposite tendency is observed in the case of PE specimens.

The T3 tensile test results and tensile stress–tensile strain curves are shown in **Table 8** and **Fig. 9**, respectively. Tensile strain is calculated from the displacement measured by LVDTs. In the case of the DCT specimens, loading could not be completed for two specimens because of delamination of the steel plates.

The T4 tensile test results and tensile stress–tensile strain curves are shown in **Table 9** and **Fig. 10**, respectively. The tensile strain is calculated from the displacement measured by LVDTs. The first cracking point could not be recognized clearly. The reason for this is thought to be the existence of the large level of bending moment caused by the fix-fix condition.

3.2.3 Bending test result
The bending test results are summarized in **Table 10**. **Figure 11** shows the bending moment–curvature rela-

Table 6 T1 tensile test results.

| DFRCC (specimen number)	First crack strength			First crack strain			Tensile strength			Strain at max.		
	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA(6)	3.72	0.84	22.5	0.021	0.003	16.5	5.00	0.47	9.4	2.697	0.657	24.3
PE(3)	3.01	0.54	17.9	0.015	0.006	40.0	4.85	0.52	10.7	1.283	0.309	24.1
HB(3)	2.32	0.17	7.3	0.015	0.003	16.4	4.37	0.63	14.3	0.705	0.299	42.4
DCT(3)	13.69	0.93	6.8	0.032	0.012	37.4	15.27	1.03	6.7	0.528	0.265	50.2
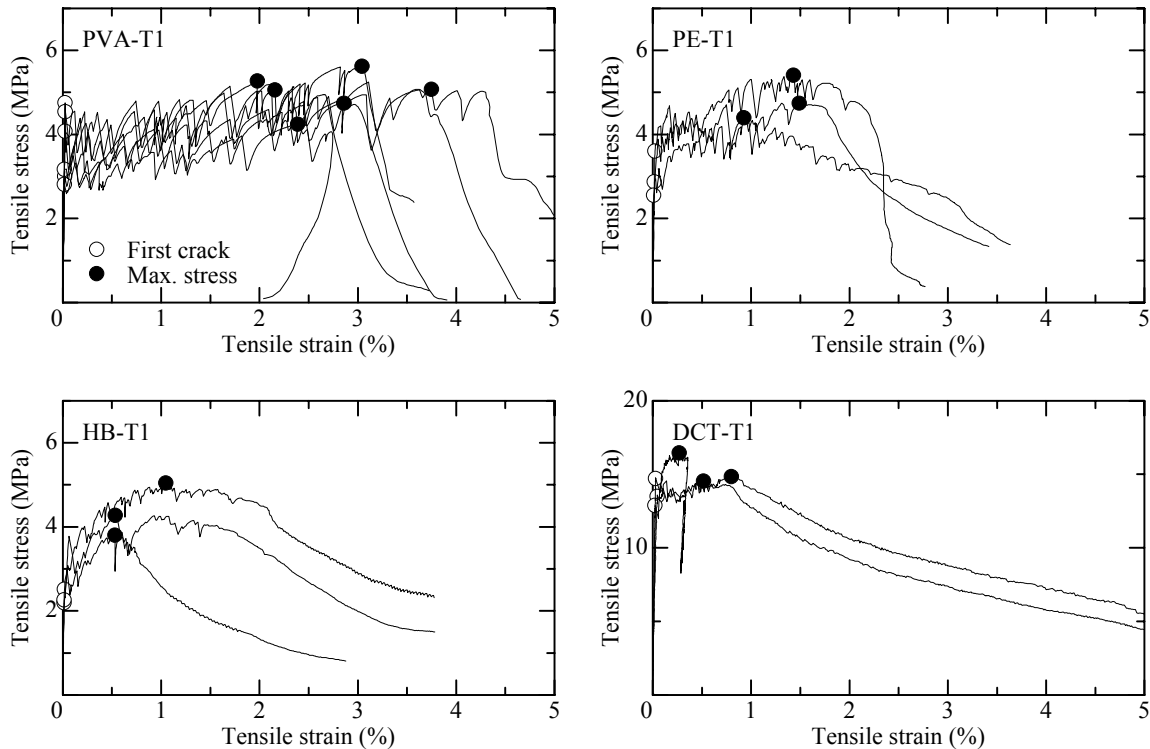
Fig. 7 T1 tensile test results.

tionships. The curvature was calculated from the measured strain obtained by two LVDTs set at the pure bending moment region. Some specimens failed at the outside of the LVDTs. These specimen data were excluded from the results. "Deflection hardening" behavior can be observed in all the tested specimens. Generally speaking, the maximum moment and curvature at the maximum moment obtained for the horizontal compacting specimens (B-H) are larger than those of the vertical compacting specimens (B-V).

3.3 Comparisons of test results
3.3.1 Comparisons of tensile test results
The test results of first crack strength and strain, tensile strength and strain at maximum stress obtained by each tensile test method are compared in **Fig. 12**. The plot symbols are distinguished by the type of DFRCC and horizontal axis indicates test method. The vertical lines extending from the plot symbols indicate the range of standard deviation.

A clear tendency for the first crack strength and strain

cannot be recognized in the case of the tensile test method. The tensile strength is observed to increase in the order of T1>T2-H>T2-V=T3>T4, except for PE specimens. The tensile strain at the maximum stress obtained by T1 and T2-H is larger than other test methods.

The tensile characteristics can be seen to differ for the four types of test method and compacting direction. As expected, the tensile strength and tensile strain at maximum stress obtained from T1 specimens show a higher level than for other test methods. This tendency is considered to be due to the 2-dimensional fiber orientation. Comparing the compacting direction, specimen T2-H has higher strength and strain than specimen T2-V. The reason for the difference in compacting direction is thought to be due to the fact that the fiber orientation is affected by the flowing direction during casting. The coefficient of variation for tensile strength ranges from 5% to 15%, the same range as in the case of the compression test. The coefficient of variation for strain shows scattering greater than that of tensile strength. It can be

Table 7 T2 tensile test results.

| DFRCC (Specimen number)		First crack strength			First crack strain			Tensile strength			Strain at max.		
		Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA	H(2)	2.47	0.12	5.0	0.015	0.002	14.5	4.18	0.20	4.9	2.380	0.417	17.5
	V(1)	2.51	-	-	0.006	-	-	2.87	-	-	0.769	-	-
PE	H(1)	3.86	-	-	0.018	-	-	3.86	-	-	0.018	-	-
	V(2)	5.02	0.56	11.2	0.024	0.002	7.4	5.06	0.50	9.8	0.253	0.322	127.4
HB	H(2)	3.42	0.66	19.2	0.018	0.001	4.8	3.54	0.50	14.1	0.217	0.182	84.0
	V(2)	2.51	0.36	14.3	0.012	0.005	39.8	2.51	0.36	14.2	0.017	0.012	69.4
DCT	H	Delamination of end plate											
	V												
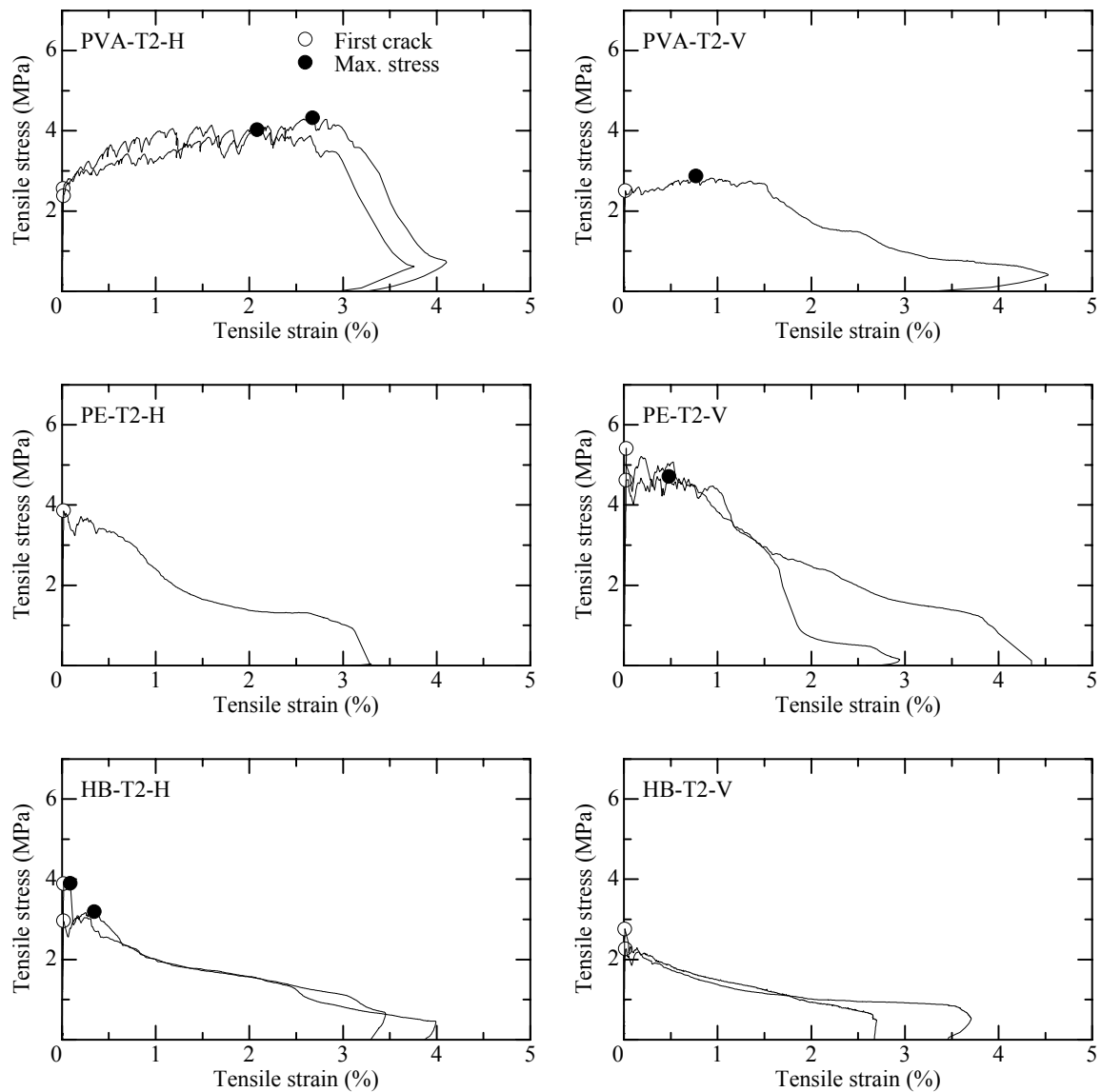
Fig. 8 T2 tensile test results.

said that it is impossible to evaluate the tensile characteristics of materials that show 100% or larger scattering in COV. Furthermore, it may be said that strain at maximum stress is not suitable for expressing the tensile deformation capacity of DFRCC.

3.3.2 Comparisons of bending test results
The test results of first crack moment and curvature, maximum moment and curvature at maximum moment obtained by the bending test are compared in **Fig. 13**. The plot symbols are distinguished by the type of

Table 8 T3 tensile test results.

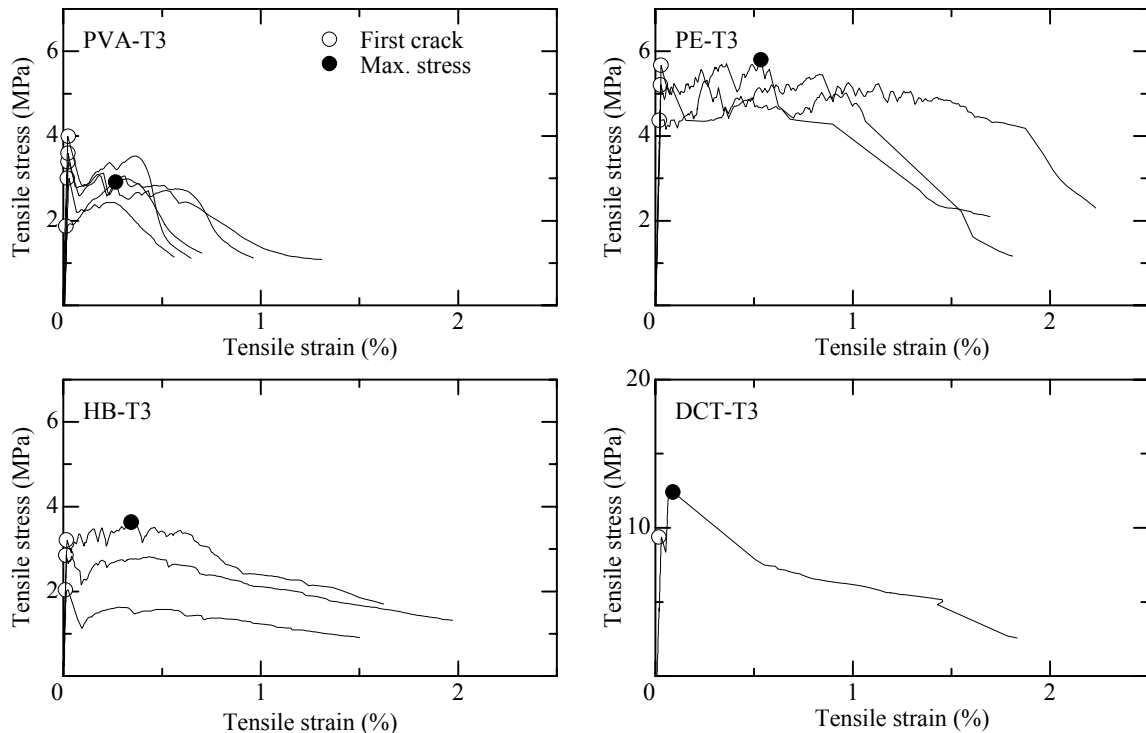| DFRCC (Specimen number)	First crack strength			First crack strain			Tensile strength			Strain at max.		
	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA(5)	3.17	0.81	25.5	0.021	0.005	23.1	3.38	0.44	13.1	0.071	0.108	151.6
PE(3)	5.08	0.66	13.0	0.025	0.004	16.9	5.56	0.31	5.6	0.196	0.293	149.4
HB(3)	2.70	0.60	22.3	0.013	0.003	23.1	2.84	0.80	28.1	0.122	0.192	156.9
DCT(1)	9.38	-	-	0.017	-	-	12.41	-	-	0.089	-	-

Fig. 9 T3 tensile test results.

DFRCC and the horizontal axis indicates the compacting direction. The vertical lines extending from the plot symbols indicate the range of standard deviation.

Clear tendencies in first crack moment and curvature cannot be recognized for the compacting direction. The maximum moments obtained for the B-H specimens are a little larger than those of the B-V specimens. The curvatures at the maximum moment obtained for the B-H specimens show remarkably larger values than those obtained for the B-V specimens. The same tendency is evidenced through the tensile test for the compacting direction.

3.3.3 Comparisons between tensile test results and bending test result

The stress distribution assumption is essential for a discussion of the comparisons between tensile characteristics and bending characteristics. In the case of cementitious composites, which have compressive strength as ten or more times greater than their tensile strength, and several percent tensile strain capacity, maximum moment in the pure bending field can be determined by tensile

strain at maximum tensile stress. At the maximum moment, compressive strain is smaller than the strain at maximum compressive stress. Two types of stress distribution are assumed as shown in **Fig. 14** for the purpose of inverse analysis from bending test results to tensile characteristics. In Case 1, first crack tensile strength and maximum tensile strength is determined from the moment at first crack and at maximum moment, respectively. In Case 2, stress distribution is supposed to be uniform in the tensile side, and only tensile strength is calculated from the maximum moment. In both cases, tensile strain at maximum tensile stress (ultimate strain) is determined by the curvature at the maximum moment. The compressive stress distribution is supposed to have an elastic region.

Table 11 and **Table 12** show the calculation results in Case 1 and Case 2, respectively. Comparing the calculated values between Case 1 and Case 2, no remarkable difference is recognized in tensile strength and ultimate strain except for the DCT specimens. Because bending test specimens have the same sectional dimensions as T2 tensile test specimens, it is proper to compare the calcu-

Table 9 T4 tensile test results.

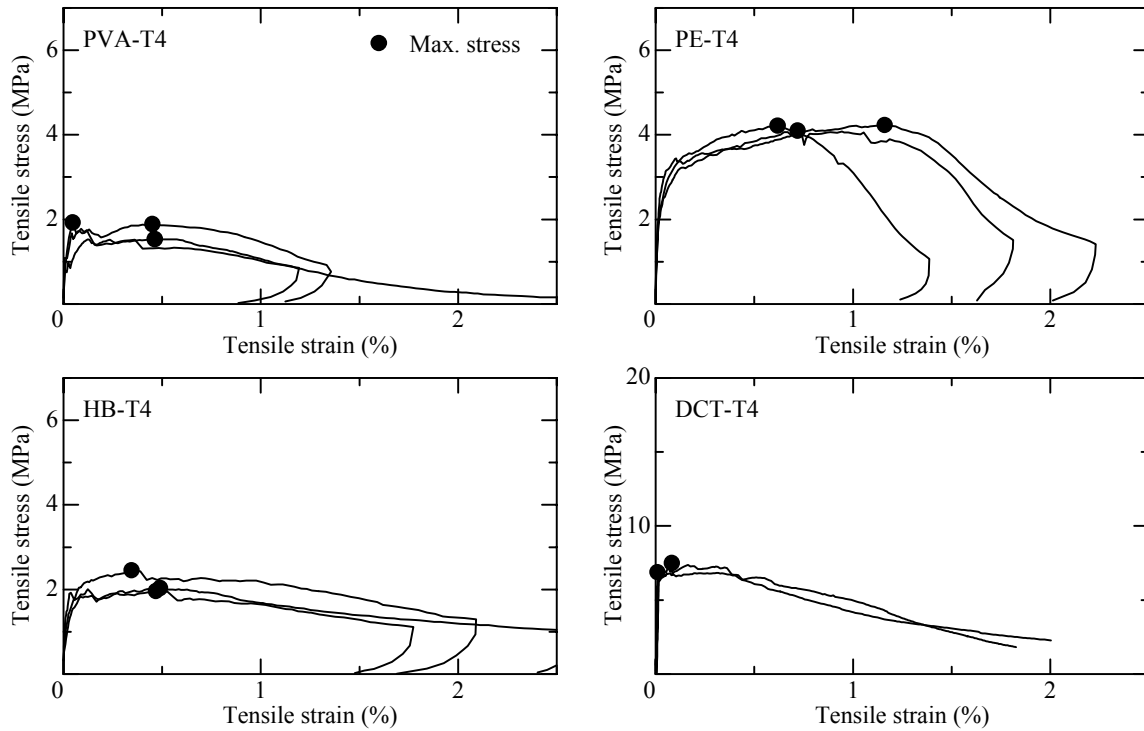| DFRCC	Tensile strength			Strain at max.		
(Specimen number)	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA(3)	1.78	0.22	12.2	0.320	0.234	73.1
PE(3)	4.18	0.07	1.7	0.833	0.287	34.5
HB(3)	2.15	0.27	12.3	0.437	0.076	17.3
DCT(2)	7.18	0.44	6.1	0.045	0.049	110.0

Fig. 10 T4 tensile test results.

lated values with T2 tensile test results. Comparing **Table 11**, **Table 12** and **Table 7**, differences between the type of DFRCC and compacting directions show the same tendencies as those observed in the tensile test results. In these test results, the difference between tensile test results and calculated values is in the data scattering range.

4. Modeling of tensile stress–tensile strain relationship

Some examples of tensile stress–tensile strain relationship models for DFRCC are shown in **Fig. 15**. The modeling aims are identification of DFRCC and the use of models for analysis and design of DFRCC members and structures. In principle, a suitable model should be

Table 10 Bending test results.

| DFRCC (specimen number)		First crack						Maximum load					
		Moment			Curvature			Moment			Curvature		
		Average (kN·m)	SD (kN·m)	COV (%)	Average (μ/mm)	SD (μ/mm)	COV (%)	Average (kN·m)	SD (kN·m)	COV (%)	Average (μ/mm)	SD (μ/mm)	COV (%)
PVA	H(3)	0.442	0.137	30.9	4.7	1.8	38.5	1.535	0.145	9.4	349.2	96.3	27.6
	V(3)	0.461	0.157	34.0	4.5	2.9	64.4	1.333	0.243	18.2	173.9	119.5	68.7
PE	H(1)	0.519	-	-	3.3	-	-	2.212	-	-	269.6	-	-
	V(2)	0.436	0.089	20.3	2.8	0.1	5.1	1.468	0.686	46.7	137.6	96.8	70.4
HB	H(3)	0.400	0.065	16.2	5.9	4.1	68.8	1.531	0.531	34.7	213.4	147.6	69.2
	V(2)	0.288	0.026	9.0	1.9	0.7	37.2	1.013	0.313	30.9	90.0	63.1	70.1
DCT	H(2)	2.154	0.088	4.1	5.0	0.1	2.8	4.518	0.117	2.6	141.2	24.1	17.1
	V(3)	2.331	0.095	4.1	6.7	4.1	61.0	3.243	0.615	19.0	72.0	39.5	54.9
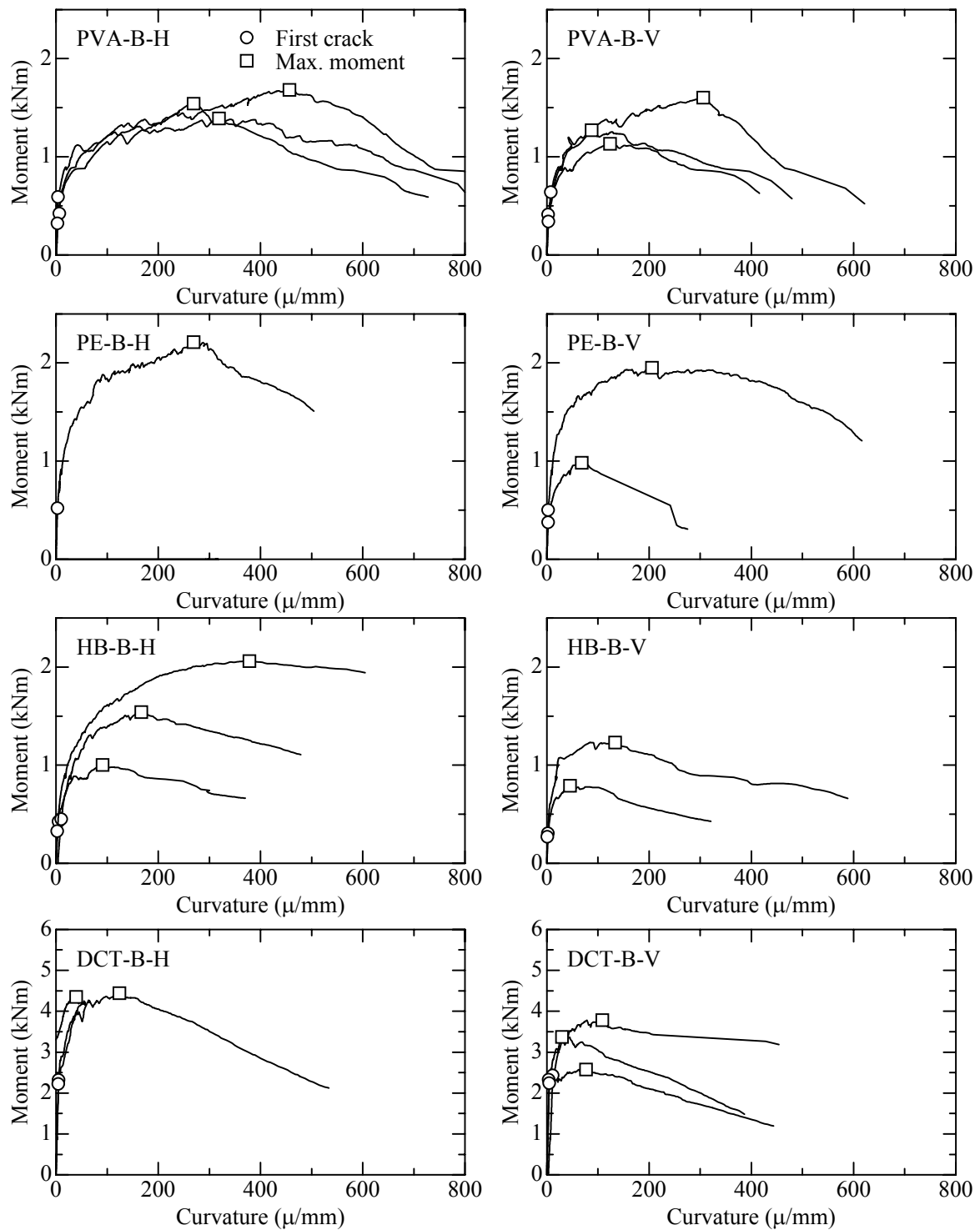
Fig. 11 Bending test results.

selected for the purpose of suitable use. For structural application and evaluation, bi-linear, elastic-plastic and rigid-plastic models are considered sufficient for expressing DFRCC characteristics. If detailed cracking behavior such as crack width and crack intervals is required for analysis and design, tensile stress–strain models are not adaptable for evaluation. The tensile

strain gives the average value of multiplication of the crack width and the reciprocal number of the crack interval.

As an extreme example, the rigid-plastic model is sufficient for evaluating only the strength capacity of DFRCC members such as beams, columns, walls and beam-column joints. For the sake of evaluation and
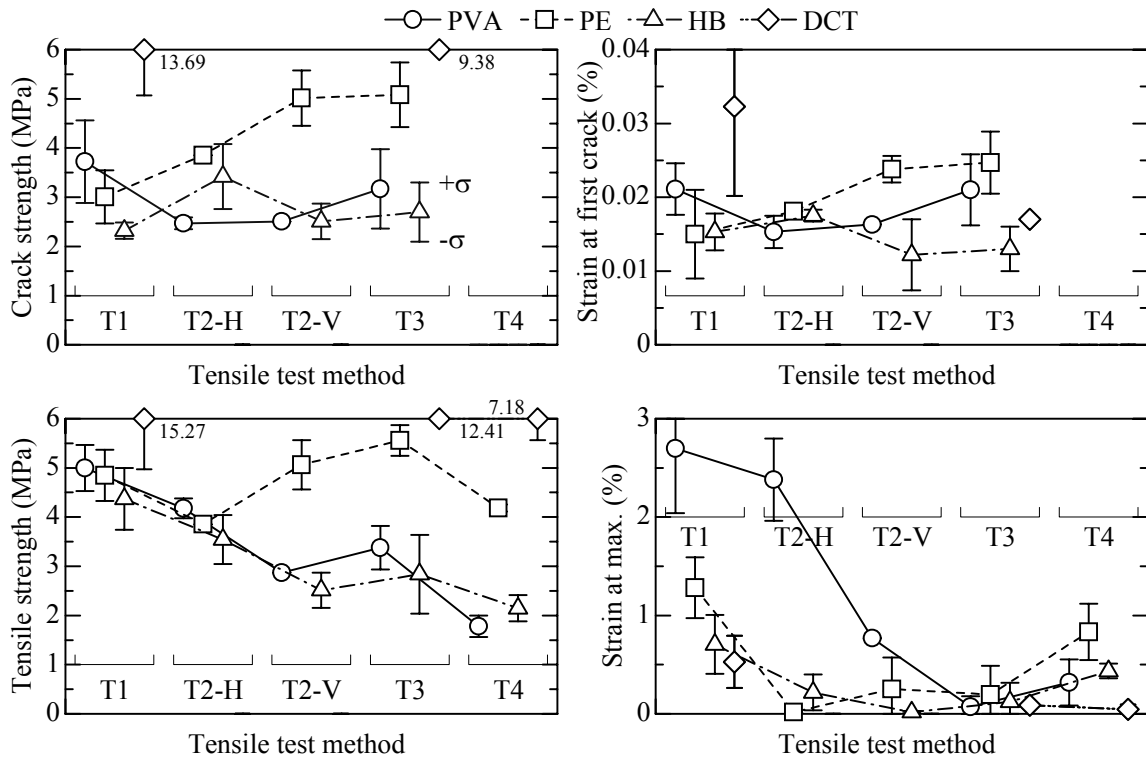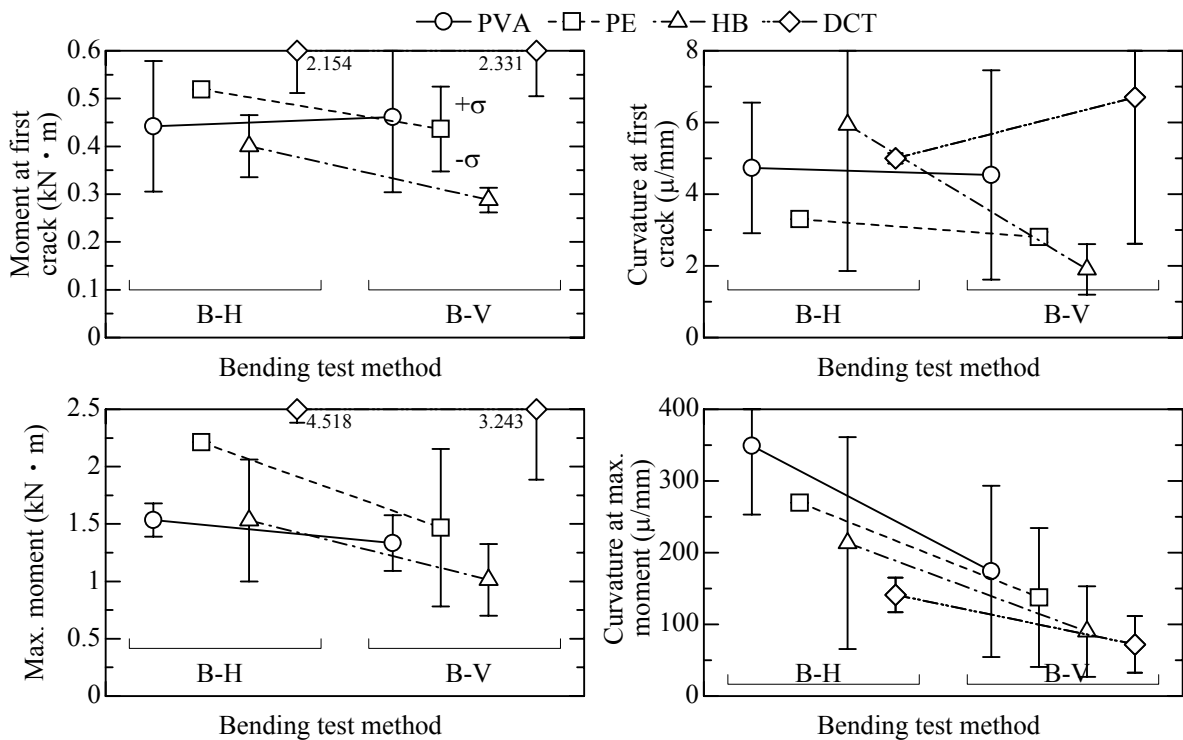
Fig. 12 Comparisons of tensile test results.

Fig. 13 Comparisons of bending test results.

calculation simplicity, unknowns had better be not so many. It can be said that material characteristics have insensitive effect on structural performance in case of complicated stress fields because of redistribution of stress.

5. JCI proposal for tensile characteristics evaluation method

The Japan Concrete Institute Standard Committee de-cided to discuss the possibility of setting up a standard
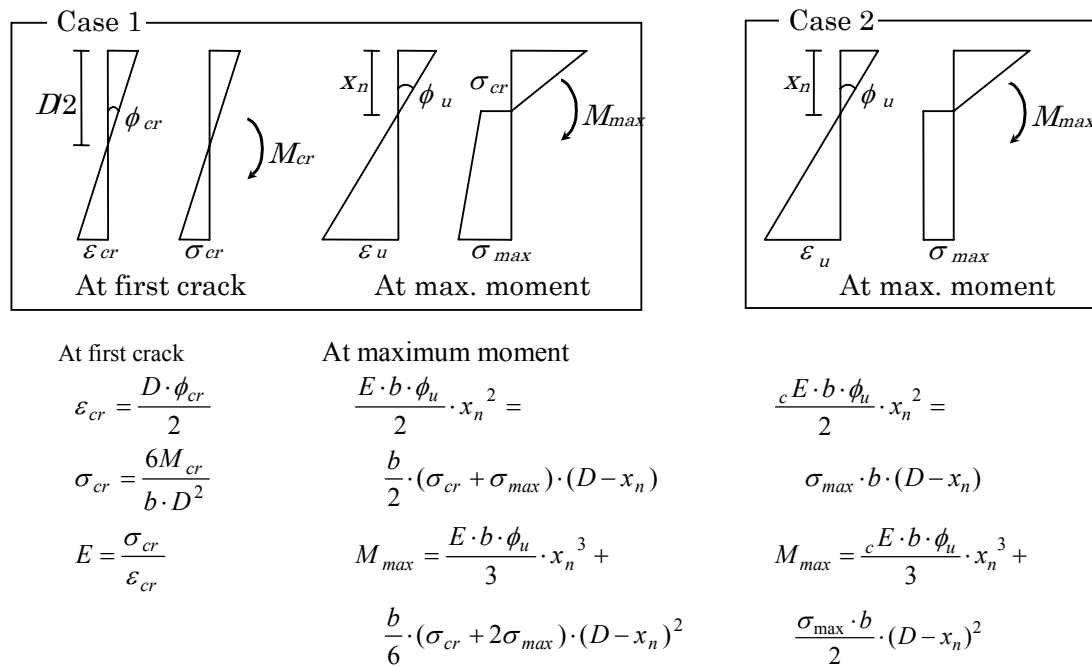
At first crack

$$\varepsilon_{cr} = \frac{D \cdot \phi_{cr}}{2}$$

$$\sigma_{cr} = \frac{6M_{cr}}{b \cdot D^2}$$

$$E = \frac{\sigma_{cr}}{\varepsilon_{cr}}$$

At maximum moment

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

$$M_{max} = \frac{E \cdot b \cdot \phi_u}{3} \cdot x_n^{\,3} +$$
$$\frac{b}{6} \cdot (\sigma_{cr} + 2\sigma_{max}) \cdot (D - x_n)^2$$

$$\frac{_cE \cdot b \cdot \phi_u}{2} \cdot x_n^{\,2} =$$
$$\sigma_{max} \cdot b \cdot (D - x_n)$$

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

Fig. 14 Assumption of stress distribution.

Table 11 Tensile characteristics calculated from bending test results (Case 1).

DFRCC		First crack strength			First crack strength / strain			Tensile strength			Ultimate strain		
		Average (MPa)	SD (MPa)	COV (%)	Average (GPa)	SD (GPa)	COV (%)	Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA	H	2.65	0.82	30.9	12.0	4.3	35.9	3.75	0.70	18.7	3.07	0.92	29.9
	V	2.77	0.94	34.0	13.8	4.2	30.8	3.14	0.30	9.4	1.46	1.01	69.3
PE	H	3.11	-	-	18.9	-	-	5.82	-	-	2.36	-	-
	V	2.62	0.53	20.3	18.6	2.9	15.4	3.66	1.95	53.2	1.18	0.88	74.3
HB	H	2.40	0.39	16.2	10.6	5.6	52.9	4.16	1.82	43.8	1.79	1.40	78.6
	V	1.73	0.16	9.0	19.2	5.5	28.7	2.54	0.92	36.2	0.78	0.59	75.7
DCT	H	12.92	0.53	4.1	51.7	3.6	6.9	8.62	0.63	7.3	1.19	0.21	17.8
	V	13.99	0.57	4.1	50.8	22.8	44.8	3.91	2.43	62.0	0.57	0.34	60.1

Table 12 Tensile characteristics calculated from bending test results (Case 2).

DFRCC		Tensile strength			Ultimate strain		
		Average (MPa)	SD (MPa)	COV (%)	Average (%)	SD (%)	COV (%)
PVA	H	3.33	0.31	9.2	3.10	0.90	29.2
	V	3.01	0.48	16.0	1.48	1.06	72.0
PE	H	4.84	-	-	2.37	-	-
	V	3.27	1.48	45.3	1.18	0.86	72.5
HB	H	3.37	1.11	33.0	1.86	1.35	72.6
	V	2.30	0.64	27.8	0.76	0.55	73.1
DCT	H	10.15	0.17	1.7	1.20	0.22	18.4
	V	7.63	1.59	20.8	0.59	0.35	59.2

test method for the evaluation of tensile characteristics for DFRCC and established a WG on the DFRCC standard test method for this purpose. The base of discussion was the report of the Technical Committee for DFRCC and the results of JCI's round robin test described in Chapter 3.

In the WG discussions, it was recognized anew that the tensile characteristics obtained from the uniaxial tension test differ according to the test method and type of DFRCC. The dimensions and shape of specimens, boundary conditions of loading, and compacting direction all influence the test results. The following items were mainly discussed in this WG.

(a) Difficulties of uniaxial tensile test as a standard test method

(b) Treatment of the DFRCC that does not have strain hardening branch

(c) Adaptability of strain-based evaluation for cracked materials

(d) Relationship between direct tensile characteristics and bending characteristics

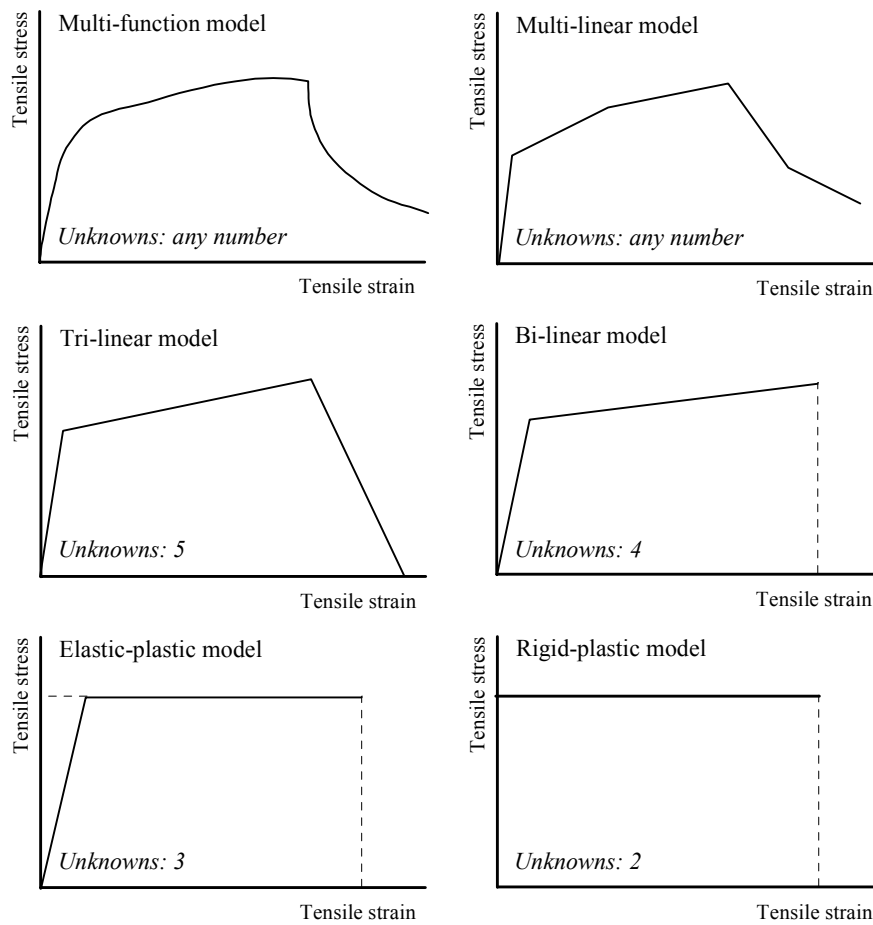In the discussions of the WG, it was pointed out that

Fig. 15 Tensile stress–strain models.

the same results have to be obtained by using a standard method in all cases, regardless of the testing machine and operator. As mentioned in Chapter 2, the uniaxial tension test requires special jigs and molds. Therefore, it is difficult to establish a standard test method using the uniaxial tension test without special techniques. In addition, precise execution of the uniaxial tension test requires a great deal of time and labor. An easier test method is required considering daily check for quality control at the mixing plants as same as compression test of concrete.
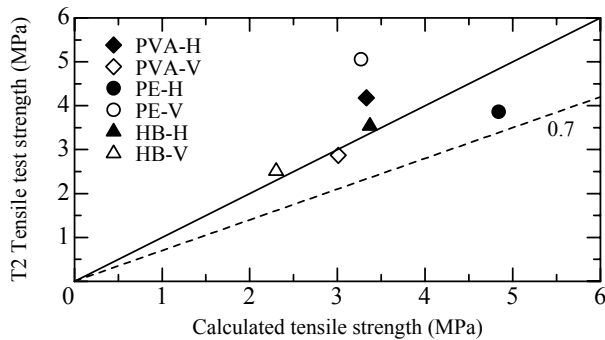

Fig. 16 Comparison between calculated tensile strength and T2 test results.

For a strain hardening-type DFRCC, the tensile strength and ultimate tensile strain evaluated by inverse analysis from the bending test results with the assumption of the stress–strain model of bi-linear or elastic–plastic generally correspond to the tensile stress and strain at the maximum point obtained by the uniaxial tension test, respectively. For a strain softening-type DFRCC, the tensile strength and ultimate tensile strain evaluated by these models vary depending on the extent of softening branch. It is certainly clear that distinction between hardening-type and softening-type DFRCC is impossible based only on the bending test results.

Demands for DFRCC vary by types of applications, as described in Chapter 1. Thus, the evaluation method must be changed to match the application. In other words, tensile characteristic evaluation without considering the intended use of DFRCC is meaningless.

As a result of discussions, only a test method for obtaining bending moment–curvature curves using a 4-point bending test was established. The applicable fiber-reinforced cementitious composites are limited to those in which several separated plural cracks occur at the pure bending region corresponding to discussion item (c). The evaluation method for tensile strength and ultimate strain was added as an appendix of non-mandatory

information. The standard is designed from the stand-point that the evaluation method should be selected in a suitable way by each user. For example, these test and evaluation methods are suitable for quality control use for DFRCC, which has a strain-hardening branch.

Figure 16 shows an example of evaluation using the JCI standard method. The plotted values have already been shown in **Table 7** and **Table 12**. The relationship between the uniaxial tension test results and calculated values from the bending test results may be considered to vary according to the type of DFRCC. To find out the answer for discussion item (d), more data and further research are necessary.

The JCI Standard titled "Method of test for bending moment–curvature curve of fiber-reinforced cementitious composites" and its commentary are presented in this issue of the Journal of Advanced Concrete Technology.

6. Conclusions

Four types of uniaxial tension test methods for four types of DFRCC were performed in the round robin test as one of the projects of the Japan Concrete Institute Technical Committee (JCI-TC) on DFRCC. There are differences in the obtained results according to the testing method parameters, such as dimensions and shape of specimens, boundary conditions, and compacting direction of DFRCC. The relationships between the tensile test results and tensile characteristics calculated from the bending test results are discussed. The Japan Concrete Institute standard for the test method using the 4-point bending test is introduced. This standard was evolved through discussions of the JCI-TC and based on round robin test results. This method is considered to indicate one example of evaluation method of DFRCC tensile characteristics.

Demands for DFRCC vary according to the type of application. An evaluation method suitable for the investigation of DFRCC characteristics to ensure that the requirements for the intended application are met should be selected. Further research to enable the effective use of DFRCC for actual applications is hoped for.

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