New simple method for quality control of Strain Hardening Cementitious Composites (SHCCs)

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ABSTRACT: As emerging advanced construction materials, strain hardening cementitious composites (SHCCs) have seen increasing field applications recently to take advantage of its unique tensile strain hardening behavior, yet existing uniaxial tensile tests are relatively complicated and sometime difficult to implement, particularly for quality control purpose in field applications. This paper presents a new simple inverse method for quality control of tensile strain capacity by conducting beam bending test. It is shown through a theoretical model that the beam deflection from a flexural test can be linearly related to tensile strain capacity. A master curve relating this easily measured structural element property to material tensile strain capacity is constructed from parametric studies of a wide range of material tensile and compressive properties. This proposed method (UM method) has been validated with uniaxial tensile test results with reasonable agreement. In addition, this proposed method is also compared with the Japan Concrete Institute (JCI) method. Comparable accuracy is found, yet the present method is characterized with much simpler experiment setup requirement and data interpretation procedure. Therefore, it is expected that this proposed method can greatly simplify the quality control of SHCCs both in execution and interpretation phases, contributing to the wider acceptance of this type of new material in field applications.

1 INRODUCTION

In the past decade, great strides have been made in developing strain hardening cementitious composite (SHCC), characterized by its unique macroscopic pseudo strain hardening behavior after first cracking when it is loaded under uniaxial tension. SHCCs, also referred to as high performance fiber reinforced cementitious composites (HPFRCCs, Naaman and Reinhardt 1996), develop multiple cracks under tensile load in contrast to single crack and tension softening behavior of concrete and conventional fiber reinforced concrete. Multiple cracking provides a means of energy dissipation at the material level and prevent catastrophic fracture failure at the structural level, thus contributing to structural safety. Meanwhile, material tensile strain hardening (ductility) has been gradually recognized as having a close connection with structural durability (Li 2004) by suppressing localized cracks with large width. Many deterioration and premature failure of infrastructure can be traced back to the brittle nature of concrete. Therefore, SHCCs are considered a promising material solution to the global infrastructure deterioration problem and tensile ductility is the most important property of this type of material.

Engineered Cementitious Composites (ECC, Li 1993) is a unique representative of SHCCs, featuring superior ductility (typically > 3%, 300 times that of normal concrete or FRC) (Li and Kanda 1998; Li et al 2001), tight crack width (less than 80μm, Li 2003), and relatively low fiber content (2% or less of short randomly oriented fibers). A typical tensile stress-strain curve of ECC is shown in Figure 1. It attains high ductility with relatively low fiber content via systematic tailoring of the fiber, matrix and interface properties, guided by micromechanics principles. Enhanced with such high tensile ductility

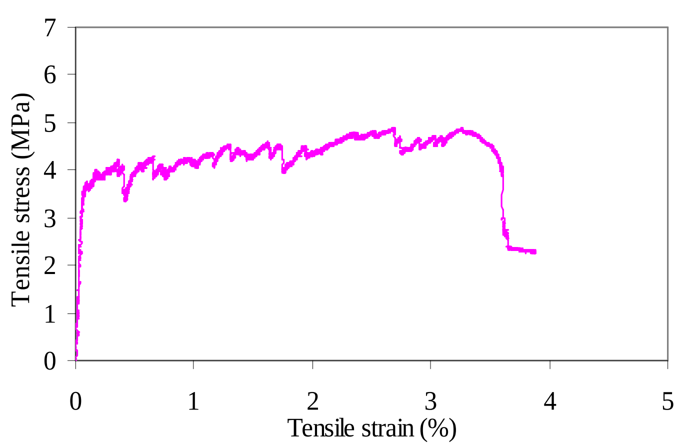

Figure 1. Typical tensile stress-strain curve of ECC.

and/or tight crack width, ECC has demonstrated superior energy dissipation capacity, high damage tolerance, large deformation capacity, and exceptional durability in many recent experimental investigations (Li 2005). As a result, ECC is now emerging in the field and has seen increasing infrastructure applications, such as dam repair, bridge deck overlay and link slab, coupling beam in high-rise building, and other structural elements and systems (Li 2004).

As aforementioned, tensile ductility is the most important material property of SHCC, yet relatively large variation of tensile ductility was observed in the literature (Kanda et al 2002, 2006; Wang and Li 2004). To address such concern, Wang and Li (2004) have proposed using artificial flaws with prescribed size distribution as defect site initiator to create more saturated multiple cracks, resulting in more consistent tensile strain capacity among different specimens from the same batch. The overall tensile strain capacity shows much more consistent results after implantation of artificial flaws, however, the variation of tensile strain capacity is still relatively large when compared with that of other properties, e.g., first cracking strength. Therefore, test method for quality control of SHCCs onsite should logically focus on tensile strain capacity due to its importance in governing structural response and potentially large variability.

While most characterization of the tensile behavior of SHCCs was carried out using uniaxial tensile test (UTT) in academia, this method is generally considered to be complicated, time-consuming and require advanced equipment and delicate experimental skills. Therefore, it is not suitable for onsite quality control purpose (Stang and Li 2004, Ostergaard et al 2005, Kanakubo 2006). First, special fixtures and/or treatments for the ends of specimens are usually needed in order to transfer tensile loads. Furthermore, the specimen is sensitive to stress concentration induced by misalignment and can fail near the end prematurely. Last but not least, realistic dimensions for specimens large enough to have 3-dimensional random fiber orientation make the UTT even more difficult to conduct.

As a simpler alternative to the UTT, four point bending test (FPBT) was proposed by Stang and Li (2004) for quality control on construction sites, provided that an appropriate interpretation procedure for the test result is available. FPBT, in which the mid-span of the specimen undergoes constant bending moment, may be carried out to determine the moment-curvature or moment-deflection curves. This type of test is much easier to set up and conduct in comparison to UTT, and a large amount of experience in bending test has been accumulated in the user community of cementitious materials. The ultimate goal of this test is to use the moment-curvature or moment-deflection curves so determined to invert for the uniaxial tensile properties. It should be noted, however, that the bending test is not meant to determine whether the material has tensile strain-hardening behavior or tension-softening behavior, but rather to constrain the tensile material parameters, e.g. the tensile strain capacity, as part of the quality control process in the field.

Inverse analyses for FPBT have recently been attempted by Technical University of Denmark (DTU) and Japan Concrete Institute (Ostergaard et al 2005; Kanakubo 2006) with certain success. By adopting a simplified elastic-perfectly plastic tensile model, JCI method generally can predict plateau tensile strength and tensile strain capacity from the FPBT results via a sectional analysis similar to that developed by Maalej and Li (1994). On the other hand, hinge model, including both tensile strain hardening and tension softening effect, was employed in the DTU inverse method along with least square method to invert for tensile material properties from their bending response. The model can predict experimental load – deflection curve fairly well and tensile properties derived based on this method agree well with that from FEM analysis, yet no direct comparison with UTT results has been made so far.

Despite the successes mentioned above, further simplification and/or validation are necessary to make the FPBT widely accepted for quality control of SHCCs. In case of JCI method, significant improvement is needed to simplify the experimental execution and data interpretation procedure. For instance, LVDTs are required in JCI method to measure the beam curvature. This is somewhat burdensome in field conditions, considering quality control may involve a large number of specimens. Furthermore, the inverse process is not user friendly, which require relatively complicated calculation (solving cubic equation). As for the DTU method, firstly it needs complementary UTT results to truly validate the model. Secondly, the uniqueness of solution from such inverse analysis is questionable at times. Finally, the method will need to be packaged into sophisticated software, which may incur additional user cost. A simple engineering chart with reasonable accuracy may be more preferable.

Keeping these considerations in mind, this paper looks to develop a greatly simplified yet reasonably accurate inverse method for determining tensile strain capacity of SHCCs. In the following sections, parametric study to obtain the master curves for inverse analysis will be presented first. Thereafter, the experimental program consisting of both FPBT and complementary UTT will be revealed in detail. The results from FPBT will then be converted to tensile strain capacity and validated with independent UTT test results. Finally, the proposed method will be compared with JCI inverse method, followed by overall conclusions.

2 PARAMETRIC STUDY AND MASTER CURVES

2.1 *Flexural behavior model*

The flexural behavior model used in this investigation is based on the work of Maalej and Li (1994). Compared with other models, the major distinction of this model is that the contribution of tensile strain hardening property of SHCCs was included. The actual SHCC considered in the model is Polyethylene ECC (PE-ECC) material. To simplify the analysis, the stress – strain behavior of the ECC was assumed as bilinear curves in both tension and compressive. Based on a linear strain profile and equilibrium of forces and moment in a section, the relation between flexural stress and tensile strain at the extreme tension fiber (Simplified as critical tensile strain hereafter) can be determined as a function of basic material properties. Overall, the model predicts experimentally measured flexural response quite well. For more detail, the readers are referred to Maalej and Li (1994).

Based on geometrical considerations, the beam curvature can be computed as the ratio of critical tensile strain to the distance from the extreme tension fiber to the neutral axis. This can be expressed in following equation:

$$\phi = \frac{\varepsilon_t}{c} \qquad (1)$$

where ϕ, ε_t , and c are beam curvatu`re, critical tensile strain, and the distance from the extreme tension fiber to the neutral axis.

In a FPBT of SHCC material, if we assume that the curvature is approximately constant along the span length of the beam and equal to the curvature in the middle span, we can obtain a simple equation to relate the deflection of the beam to its curvature and therefore critical tensile strain. For a constant curvature, the load point deflection u for a beam having a span *L* is given by:

$$u = \frac{L^2 \cdot \phi}{9} = \frac{L^2 \cdot \varepsilon_t}{9 \cdot c} \qquad (2)$$

Since the relation between flexural stress and ε_t is already established, we can predict the flexural stress and load point deflection relation based on Equation (2). The peak flexural stress (MOR) and corresponding deflection (deflection capacity) are reached once the strain capacity of the SHCCs is exhausted either at the extreme tensile fiber or at the extreme compression fiber, which is the assumed failure criterion in this model.

Table 1. Range of material parameters used in parametric studies to construct the tensile strain capacity – deflection capacity (curvature) relation.

	Tensile properties				Compressive properties	
Material parameters	σ_{tc} (MPa)	σ_{tu} (MPa)	ε_{tu} (%)	E (GPa)	f_c' (MPa)	ε_{cp} (%)
Range	2.5~13.0	4.0~16.0	0~5	12~53	31~200	0.5~1*

Note: σ_{tc} =tensile first cracking strength; σ_{tu} = ultimate tensile strength; ε_{tu} = tensile strain capacity; E= modulus of elasticity; f_c' = compressive strength; and ε_{cp} =compressive strain capacity; Parameters are in the normal range of test results of SHCC specimens at UM and JCI; Tensile and compressive modulus of elasticity are assumed to be equal; Beam dimensions are 51x76x356mm or 100x100x400mm with span length of 305mm or 300mm for UM and JCI specimens, respectively; *: Estimated range.

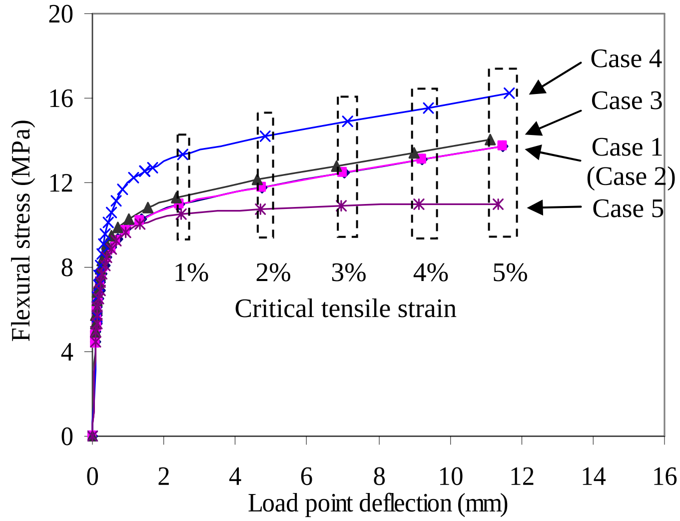

Figure 2. Parametric study for SHCCs with different material parameters (Dashed line boxes include markers corresponding to same critical tensile strain (tensile strain at the extreme tension fiber); markers are plotted on 1% strain interval after 1% strain for all cases).

2.2 *Construction of master curves*

Parametric study was conducted to investigate the influence of material uniaxial tensile and compressive properties (parametric values) on the flexural response of SHCCs based on the aforementioned flexural model. The correlation between tensile strain capacity and load point deflection was established and constructed as master curve. All tensile and compressive properties were varied within a wide range of parametric values (Table 1), covering the normal range of test results of SHCC specimens at UM and JCI (Kanakubo 2006). It is expected that the master curves based on this wide range of parametric study can be directly utilized for quality control purpose in field.

Five cases of parametric study were plotted in Figure 2 as examples, showing the flexural stress, load point deflection and corresponding critical tensile strain relation. Beam dimensions are 51x76x356mm with span length of 305mm. From the Figure, load point deflections were observed to correlate very well with critical tensile strains, regardless of the actual parametric material properties (shown in Table 2). Once the critical tensile strain reaches the tensile strain capacity, the beam reaches peak load and the corresponding load point deflection is the deflection capacity. Therefore, it appears that the deflection capacity and tensile strain capacity can be linearly correlated from above cases with variation in all major material properties.

Table 2. Assumed material properties for different cases of SHCCs.

	Tensile properties				Compressive properties	
	σ_{tc} (MPa)	σ_{tu} (MPa)	ε_{tu} (%)	E (GPa)	$f_c^{'}$ (MPa)	ε_{cp} (%)
Case 1	4.0	5.6	5%	18	50	0.005
Case 2	4.0	5.6	5%	***20***	50	0.005
Case 3	4.0	5.6	5%	18	**75**	0.005
Case 4	**5.0**	**6.6**	5%	18	50	0.005
Case 5	4.0	**4.0**	5%	18	50	0.005

Note: σ_{tc} =tensile first cracking strength; σ_{tu} = ultimate tensile strength; ε_{tu} = tensile strain capacity; E= modulus of elasticity; $f_c^{'}$= compressive strength; and ε_{cp} =compressive strain capacity.

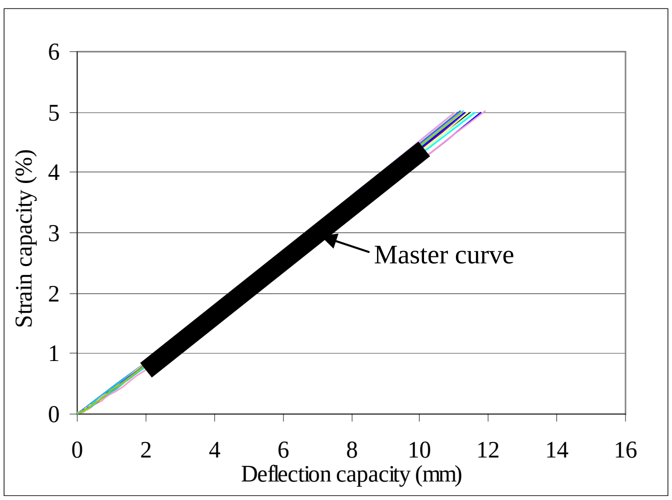

Figure 3. Tensile strain capacity –deflection capacity relation obtained from parametric study (20 cases) and simplified master curve (with uniform thickness).

The overall results from the parametric study indeed show a linear relation between tensile strain capacity and deflection capacity, as revealed in Figure 3. Totally 20 cases were investigated in the parametric study, with the range of material parameters shown in Table 1. All linear curves lie in a narrow band regardless of actual material properties, which suggests that the beam deflection capacity is most sensitive to tensile strain capacity for a fixed geometry. For ease of quality control on site, master curve was constructed as a line with uniform thickness to cover all parametric case studies, as shown in Figure 3. The top edge of the master curve is made to coincide with the upper boundary of all curves for conservativeness.

Additionally, another master curve correlating tensile strain capacity with curvature was constructed by parametric study in order to compare the proposed UM method with JCI method, in which ultimate bending moment and curvature was utilized to derive tensile strain capacity. The range of parametric values is the same as the aforementioned parametric study, as shown in Table 1. The dimension of specimen used in this parametric study is 100x100x400mm, with a span length of 300mm (JCI-S-003-2005).

Similarly, this set of master curve also characterizes a linear relation within a very narrow band regardless of actual material properties. Since curvature may be linearly correlated with deflection using Equation (2), this master curve can be easily transformed into tensile strain capacity to deflection capacity relation, even though the slope should be different from Figure 3 due to different dimensions used in the two parametric studies. In the case when specimens with different dimensions have to be used for quality control, e.g. due to different fiber length, a different set of master curve should be constructed.

2.3 *The use method of master curves*

Based on the master curves obtained from parametric study, the deflection capacity from simple beam bending test can be easily converted to material tensile strain capacity. A set of equations has been developed to simplify the conversion procedure, as shown below, where Equations (3) and (4) can be used to calculate the average tensile strain capacity and its deviation, respectively.

$$\varepsilon_{tu}^{'} = 0.46 \cdot \delta_u - 0.26 \qquad (3)$$

$$PD = 0.46 \cdot SD + 0.17 \qquad (4)$$

where $\varepsilon_{tu}^{'}$ is the predicted average tensile strain capacity (%); δ_u is the average deflection capacity obtained from FPBT (mm); *PD* is the predicted deviation for tensile strain capacity (%) and *SD* is the standard deviation of the deflection capacity (mm).

It should be noted that this equation can only apply to specimen with the same geometry and same loading conditions as that used by the authors (see Section 3). Should any of these geometry and/or loading conditions change, another set of master curves and corresponding conversion equations should be developed for that purpose. Once the proposed method (or its modified version) is standardized and widely accepted, there should be no need for change in geometry and loading conditions.

Similarly, another set of equation has also been developed to simply the conversion procedure for specimen tested according to JCI method. Equations (5) and (6) can be used to calculate the average tensile strain capacity and its deviation, respectively.

$$\varepsilon_{tu,c} = 0.0094 \cdot \phi_{u,c} - 0.26 \tag{5}$$

$$PD_c = 0.0094 \cdot SD_c + 0.16 \tag{6}$$

where $\varepsilon_{tu,c}$ is the predicted average tensile strain capacity (%); $\phi_{u,c}$ is the average curvature capacity obtained from FPBT (μ/mm); PD_c is the predicted deviation for tensile strain capacity (%) and SD_c is the standard deviation of the curvature capacity (μ/mm). The same limitation as mentioned above for Equations (3) and (4) also applies to Equations (5) and (6), except that the specimen geometry and loading profile should follow those in the JCI method.

Table 3. Mix proportion for different SHCCs.

	Cement	Sand	FA	W/C	SP	Fiber
PVA-ECC 1	1	0.8	1.2	0.27	0.013	0.02
PVA-ECC 2	1	1.1	2	0.26	0.014	0.02
PVA-ECC 3	1	1.4	2.8	0.26	0.016	0.02
PVA-ECC 4*	-	-	-	0.46	-	0.019
Ductal*	-	-	-	0.22	-	0.02

Note: FA= fly ash; W/C=water/cementitious materials (including cement and fly ash); SP=superplasticizer; *: Data from JCI round robin test (Kanakubo, 2006)

Table 4. Material tensile and compressive properties from experiment for different SHCCs.

	σ_{tc} (MPa)	σ_{tu} (MPa)	ε_{tu} (%)	f_c' (MPa)
PVA-ECC 1	4.6±0.3 (7%)	5.3±0.6 (11%)	2.1±1.1 (52%)	54.6±6.5 (12%)
PVA-ECC 2	3.9±0.5 (13%)	4.6±0.2 (4%)	3.5±0.3 (9%)	46.0±3.8 (8%)
PVA-ECC 3	4.0±0.2 (5%)	4.9±0.1 (2%)	3.7±0.4 (11%)	37.5±1.7 (5%)
PVA-ECC 4*	3.7±0.8 (21%)	5.0±0.5 (10%)	2.7±0.7 (26%)	31.3±0.8 (3%)
Ductal*	13.7±0.9 (7%)	15.3±1.0 (7%)	0.5±0.3 (60%)	198.0±3.7 (2%)

Note: σ_{tc} =tensile first cracking strength; σ_{tu} = ultimate tensile strength; ε_{tu} = tensile strain capacity; f_c' = compressive strength; *: Experimental data from JCI round robin test (Kanakubo, 2006); Number in parenthesis is coefficient of variation (COV).

3 EXPERIMENTAL PROGRAM

3.1 *Materials, specimen preparation and testing*

The mix proportion of SHCC materials investigated in this study is shown in Table 3, including PVA-ECC 1, 2 and 3. These SHCC materials feature high amount of fly ash in the mix proportion, with fly ash to cement ratios of 1.2, 2.0, and 2.8, respectively. Additionally, PVA-ECC 4 and Ductal from JCI round robin test (Kanakubo 2006) are also listed in Table 3, which will be used for comparison between UM method and JCI method.

A Hobart mixer was used in this investigation, with a full capacity of 12 liters. All beam, uniaxial tensile and compressive specimens were cast from the same batch. At least 3 specimens were prepared for each test. After demolding, all specimens were cured in a sealed container with about 99% humidity under room temperature for 28 days before testing. Four point bending test was conducted with a MTS 810 machine. The beam specimen has a dimension of 356mm long, 50 mm high, and 76 mm deep, all dimensions are at least 4 times that of the PVA fiber length (12mm), which is the largest length scale among the ingredients of PVA-ECC. The loading span between two supports is 305mm with a constant moment span length of 102mm. The beam was tested under displacement control at a loading rate of 0.02 mm/second. The flexural stress was derived based on simple elastic beam theory and the beam deflection at the loading points was measured from machine displacement directly. The test setup is shown in Figure 4 (a) in comparison with the JCI method (Figure 4 (b)).

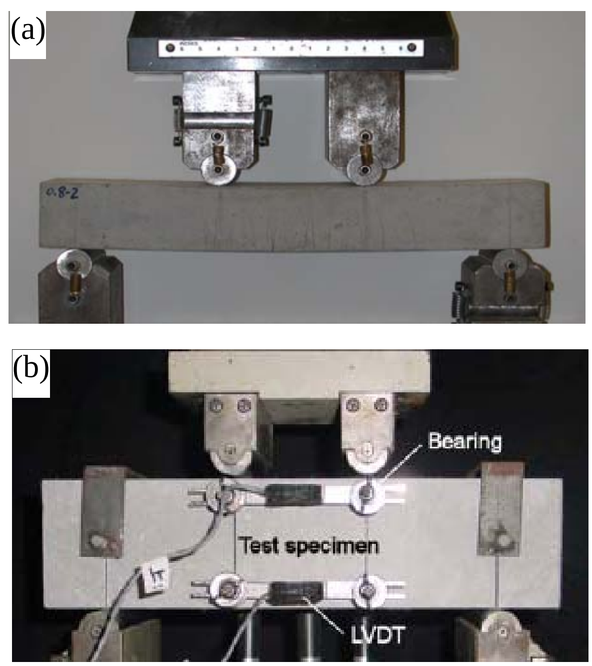

Figure 4. Comparison of test setup for the (a) UM method and (b) JCI method.

3.2 *Experimental results*

The material tensile and compressive properties for different SHCCs can be found in Table 4. With increasing amount of fly ash in PVA-ECC 1-3, the compressive strength continues to decrease as expected, yet PVA-ECC 3 still has a compressive strength of about 38 MPa. For all SHCCs the typical coefficient of variations (COV) of first cracking strength and ultimate tensile strength are less than 15%, similar to that of compressive strength. Conversely, the COV of tensile strain capacity are in the range of 26%-60% except for PVA-ECC 2 and 3, where the robustness of tensile ductility increased (in the form of reduced COV) due to the usage of high volume fly ash (Wang 2005). This general trend – relatively low COV for tensile strength and high COV for tensile strain capacity can also be found in Kanakubo (2006). This further confirmed the rationale of quality control for the tensile strain capacity instead of tensile strength.

PVA-ECC 1-3 show typical deflection hardening behavior under FPBT. More and more saturated microcrack is revealed from PVA-ECC 1 to 3, associated with gradual increase of deflection capacity (Table 5). The modulus of rupture for PVA-ECC 1-3 ranges from 10-12 MPa, about 2.4-3.0 times that of their first cracking strength. This is consistent with the finding of Maalej and Li (1994) that this ratio should be about 2.7 for elastic-perfectly plastic material (for tensile portion of beam), such as the PVA-ECCs investigated in this study.

Table 5. Comparison between predicted tensile strain capacity from FPBT and tensile strain capacity from UTT.

	ε_{tu} from UTT (%)	Deflection capacity from FPBT (mm)	Predicted ε_{tu} (%)	Difference between prediction and test result (%)
PVA-ECC 1	2.1±1.1	5.9±1.6	2.4±0.9	14%
PVA-ECC 2	3.5±0.3	7.2±1.3	3.1±0.8	-11%
PVA-ECC 3	3.7±0.4	9.4±0.9	4.1±0.6	11%

(Note: ε_{tu} = tensile strain capacity.)

Table 6. Comparison between uniaxial tensile test results with predictions based on the JCI method and the UM method

	ε_{tu} from UTT (%)	Curvature capacity from FPBT (μ/mm)	Predicted ε_{tu} (JCI method) (%)	Predicted ε_{tu} (UM method) (%)
PVA-ECC 4	2.7±0.7	349.2±96.3	3.1±0.9 (15)	3.0±1.1 (11)
Ductal	0.5±0.3	85.0*	0.6* (20)	0.5* (0)

(Note: *: Only two bending specimens were reported. The number in parenthesis is the difference (in percentage) between the predictions and test results from uniaxial tensile test.)

4 VALIDATION AND VERIFICATION OF THE PROPOSED METHOD

To validate the proposed inverse method, the deflection capacity obtained from FPBT is converted to tensile strain using Equations (3) and (4) (derived for the same beam size as used in the FPBT experiments) and then compared with tensile strain capacity obtained directly from uniaxial tensile test for PVA-ECC 1-3. As revealed in Table 5 and Figure 5, the tensile strain capacity derived from FPBT predicts the uniaxial tensile test results with reasonable accuracy, with a difference of less than 15%. This agreement demonstrates the validity of the proposed inverse method.

To further verify the proposed UM method, comparison between UM method and JCI method was conducted based on JCI round robin test data (Kanakubo 2006). As mentioned previously, bending test results from JCI round robin test are presented in the form of moment –curvature relation. To facilitate the comparison, the curvature capacity can be converted to tensile strain capacity using Equations (5) and (6) in UM method. Within the JCI method, the tensile strain capacity is obtained by solving following equations (JCI-S-003-2005):

$$\varepsilon_{tu,b} = \phi_u \cdot D \cdot (1 - x_{nl}) \tag{7}$$

$$x_{nl}^3 + 3x_{nl}^2 - 12m^* = 0 \tag{8}$$

$$m^* = \frac{M_{\max}}{E \cdot \phi_u \cdot B \cdot D^3} \tag{9}$$

where $\varepsilon_{tu,b}$ is the predicted tensile strain capacity (%); ϕ_u is the curvature capacity (1/mm), which can be calculated from two LVDTs measurements (Fig. 4(b)); D is depth of the test specimen (=100 mm); x_{nl} is the ratio of the distance from compressive edge (extreme compression fiber) to neutral axis over depth of test specimen, which needs to be solved from Equation (8); $M_{\max}$ is maximum moment $(N \cdot mm)$; E is the static modulus of elasticity (N/mm^2); B is the width of test specimen (100 mm). For more details, readers are referred to the Appendix to JCI-S-003-2005.

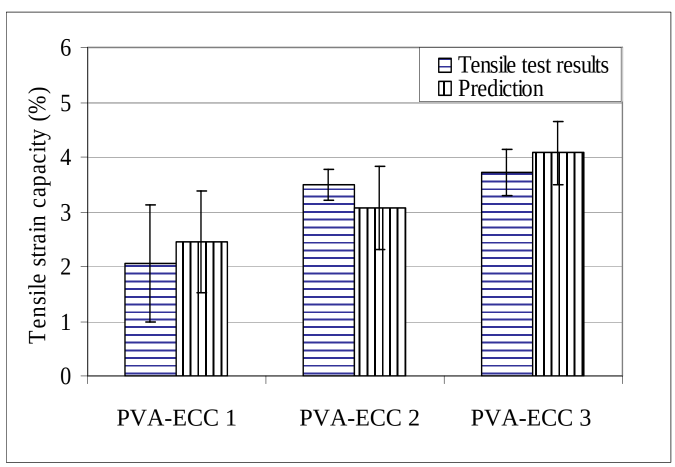

Figure 5. Comparison of tensile strain capacity from UTT test with prediction from proposed UM method for different PVA-ECCs.

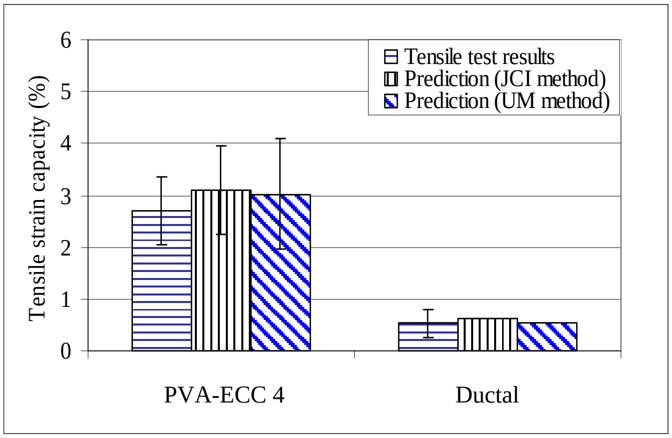

Figure 6. Comparison of tensile strain capacity from UTT with predictions from JCI method and proposed UM method for different SHCCs. (Experimental data for both UTT and FPBT are from JCI round robin test and only two FPBT specimens were reported for Ductal.)

As shown in Table 6 and Figure 6, predictions based on both the UM method and the JCI method reveal comparable results with those from uniaxial tensile tests. Furthermore, the UM method shows smaller discrepancy with the uniaxial tensile test result (Table 6) based on limited data. The consistency between the UM method and the JCI method and verification by independent JCI round robin test data further demonstrate the validity of the proposed UM method.

The advantage of the UM method over the JCI method lies in its simplicity, both in experiment and data interpretation phases. In the experiment phase, the UM method only requires machine displacement to be measured. This is not the case for the JCI method, where complicated setup such as LVDTs is needed to measure curvature, as revealed in Figure 4 (a) and (b). In the data interpretation phase, the UM method only needs a simple master curve or linear equation to convert deflection capacity directly into tensile strain capacity, while JCI method requires relatively complicated procedures (solving cubic equation) to obtain tensile strain capacity. Considering the large amount of specimens needed to be tested during construction, the UM method seems to be more suitable for quality control purpose due to its simplicity, efficiency and reasonable accuracy.

5 CONCLUSIONS

To facilitate the quality control of the strain hardening cementitious composites on site, a simplified inverse method is proposed to covert the deflection capacity from simple beam bending test to tensile strain capacity through linear transformation. The linear transformation (in the form of master curves) is derived from parametric study with a wide range of parametric values of material tensile and compressive properties based on a theoretical model. This proposed method has been experimentally validated with uniaxial tensile test results with reasonable agreement. In addition, this proposed method compares favorably with the JCI method in accuracy, but without the associated complexity.

The following specific conclusions can be drawn from this study:

1. A simple inverse method has been successfully developed to derive tensile strain capacity of SHCC from beam bending deflection capacity by using a master curve. This method is expected to greatly ease the on-site quality control for SHCC in terms of much simpler experiment setup requirement (compared with both UTT and the JCI inverse method) and data interpretation procedure (compared with the JCI method), yet with reasonable accuracy (within 15%);
2. The master curve features simple linear transformation from deflection capacity to tensile strain capacity. The master curve decouples the dependence of tensile strain capacity on the moment capacity in contrast with the JCI method where tensile strain capacity is dependent on both curvature capacity and moment capacity. Therefore, this method allows simple linear equations (Equation (3) and (4)) to be used for easy data interpretation;
3. A linear relation between the deflection capacity and the tensile strain capacity is observed based on parametric studies. All linear curves relating tensile strain capacity and deflection capacity lie in a narrow band regardless of actual material properties. This suggests that beam deflection capacity is most sensitive to tensile strain capacity for a given FPBT geometric dimensions, and much less sensitive to other properties such as compressive strength, Young’s Modulus, etc.

It should be noted that the following assumptions are made when the proposed UM method is used: (a) The tested material is truly a strain hardening type; (b) The major target for quality control for this material is tensile ductility; and (c) For this method to be most effective, a standardized beam with fixed geometric dimensions should be agreed upon by the user community.

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