Relating tensile properties with flexural properties in SHCC

S. Qian
ACE-MRL, Department of Civil Engineering, University of Michigan, U S A
School of Transportation, Southeast University, Nanjing, P R China

V. C. Li
ACE-MRL, Department of Civil Engineering, University of Michigan, U S A

J. Zhou
Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Netherlands

ABSTRACT: Strain hardening cementitious composites (SHCCs) have seen increasing field applications in past decade, yet existing quality control test methods for tensile properties are sometime difficult to implement. This paper presents a new simple inverse method for quality control of tensile strain capacity by conducting beam flexural 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. Good agreement between prediction and tensile test suggest that this method is very robust for different mixtures with variable geometry and test setup.

1 INSTRUCTION

SHCCs, also referred to as high performance fiber reinforced cementitious composites (HPFRCCs et al. 1996), develop multiple cracks under tensile load in contrast to single crack and tension softening behavior of concrete and conventional fiber reinforced concrete. In the last 15 years, SHCCs have gained a lot of attentions in infrastructural applications to overcome the brittle nature of concrete. SHCCs are considered a promising material solution to the global infrastructure deterioration problem and to infrastructure safety concerns under severe loading.

Most tensile characterization of SHCCs was carried out using uniaxial tensile test (UTT) in academia; nevertheless, this method is generally considered complicated, time-consuming and requires advanced equipment and delicate experimental skills. Therefore, it is not suitable for onsite quality control purpose (Stang & Li 2004). Stang & Li (2004) proposed that four point bending test (FPBT) may be used for quality control of tensile properties on construction sites, provided that an appropriate interpretation procedure (e.g. inverse analysis) for the bending test result is available. FPBT is much easier to set up and conduct in comparison to UTT, and extensive user experience has been accumulated in the civil engineering community.

Ostergaard et al. (2005) have proposed an inverse analysis technique for FPBT. In their method, hinge model, including both tensile strain hardening and tension softening effect, was employed 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.

On the other hand, Kanakubo (2006) also proposed an inverse analysis method. By adopting a simplified elastic-perfectly plastic tensile model, this 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 & Li (1994). Nevertheless, 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.

More recently, Qian and Li proposed another inverse method (Qian & Li 2007, 2008) in order to have simpler test setup and inverse procedure. While

their method is also based on the model by Maalej & Li (1994), it allows a simple FPBT without using LVDTs and linear transformation from deflection to tensile strain capacity. It has been shown that this method agrees well with the method proposed by Kanakubo (2006). Nevertheless, the number of mixtures for validation purpose is relatively small. In this paper, this method will be further validated by extensive data sets by Zhou et al. (2009a,b), which also have different geometry and test setup.

In the following sections, the overall procedure of inverse analysis will be briefly described. 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, overall conclusions will be drawn based on validation results.

2 PROCEDURE OF INVERSE ANALYSIS

As shown in the Figure 1, deflection capacity (deflection corresponding to peak bending stress, i.e., modulus of rupture) can be obtained from FPBT. By conducting parametric studies based on a flexural behavior model of SHCCs, master curve was constructed in terms of tensile strain capacity with respect to deflection capacity (Qian & Li 2007). Based on deflection capacity of FPBT and master curve from parametric study, tensile strain capacity of SHCCs can be derived. Additionally, a companion UTT test using specimens cast from the same batch of material is used to validate and/or verify the proposed method in terms of the accuracy of derived tensile strain capacity.
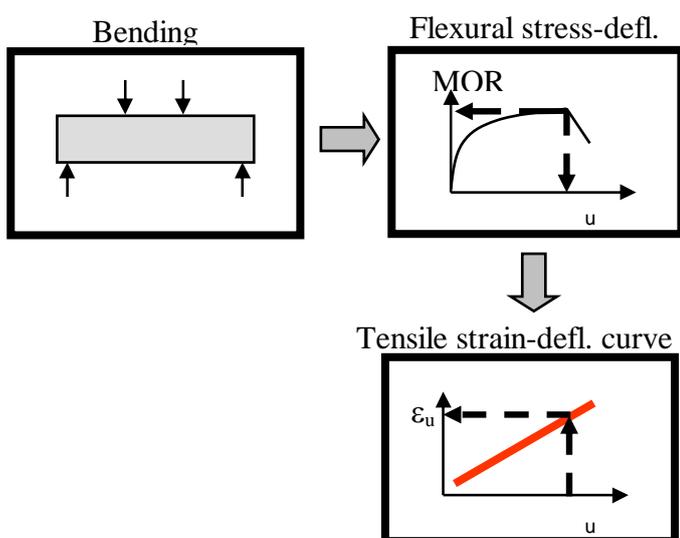

Figure 1. Procedure of inverse analysis.

Table 1. Mix proportion of ECC and concrete by weight (fiber by volume).

Material	Cement	Sand	Fly Ash	Water/ Cementitious Material	Super- plastizer	Fiber volume %
PVA-ECC1	1	0.8	1.2	0.27	0.013	2
PVA-ECC2	1	1.1	2	0.26	0.014	2
PVA-ECC3	1	1.4	2.8	0.26	0.016	2

3 EXPERIMENTAL PROGRAM

The mix proportion of SHCC materials investigated in this study is shown in Table 1, including PVA-ECC 1, 2 and 3. A Hobart mixer was used in this investigation, with a full capacity of 12 liters. All beam and uniaxial tensile specimens were cast from the same batch. The beam and uniaxial tensile specimens were cast horizontally. 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. 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.

Figure 2. Setup for uniaxial tensile test.

As shown in Figure 2, uniaxial tensile test (UTT) was also carried out to directly verify the derived tensile strain capacity from four point bending test.

The coupon specimen used herein measured 304.8 x 76.2 x 12.7 mm. Aluminum plates were glued at both ends of the coupon specimen to facilitate gripping (both ends are fixed). Tests were conducted in an MTS 810 machine with a 25 kN capacity under displacement control, with a loading rate of 0.0025mm/second throughout the test. Two external linear variable displacement transducers (LVDTs) were attached to specimen surface with a gage length approximately 180mm to measure the displacement.

Additionally, Mixture M1-6 from Zhou et al. (2009a) is listed in the Table 2. In his test, the fresh ECC was cast into six coupon specimens with the dimension of 240 mm × 60 mm × 10 mm for the four-point bending and the uniaxial tensile tests and a beam with the dimension of 160 mm × 40 mm × 40 mm for the compressive test. After 1 day curing in moulds covered with plastic paper, the specimens were demoulded and cured under sealed condition at a temperature of 20°C for another 27 days.

Their coupon specimens were evenly sawn into four pieces with the dimension of 120 mm × 30 mm × 10 mm. These specimens were used in four-point bending test (Fig. 3). The support span of the four-point bending test set-up was 110 mm and the load span was 30 mm. Two LVDTs were fixed in both sides of the test set-up to measure the flexural deflection of the specimen. The test was conducted under deformation control in the speed of 0.01 mm/s. Three measurements were done for each mixture.

Table 2. Mix proportion of ECC and concrete by weight (fiber by volume) (Jian et al. 2009a).

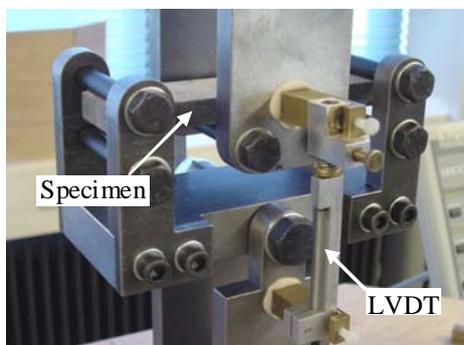| Material	Cement	Limestone powder	Blast furnace slag	Water/ powder	Super-plastizer	PVA fiber (by volume %)
M1	1	0.8	1.2	0.27	0.025	2
M2	1	1.5	1.2	0.27	0.023	2
M3	1	2	1.2	0.26	0.018	2
M4	1	3	1.2	0.26	0.018	2
M5	1	2	1	0.26	0.018	2
M6	0.6	2	1.4	0.26	0.020	2

Figure 3. Four-point bending test set-up.

A new uniaxial tensile test set-up was developed for SHCC as shown in Figure 4 (Zhou 2009a). The specimen is clamped by four steel plates, one pair at each end. Each pair of steel plates is fastened with four bolts. Two pairs of steel plates are fixedly connected to the loading device with two steel bars for each pair. Between the pairs of steel plates and the loading device, there is a ±3 mm allowance. It is used to diminish the eccentricity in the direction perpendicular to the plate of the specimen by moving the steel plates along the steel bar. The tensile force is transferred to the specimen by the friction force between the steel plates and the specimen. Four aluminum plates, 1 mm thick, are glued on both sides of the two ends of specimens in order to improve the friction force, to ensure the clumped area work together and to prevent the local damage on the specimen due to the high clumping force.
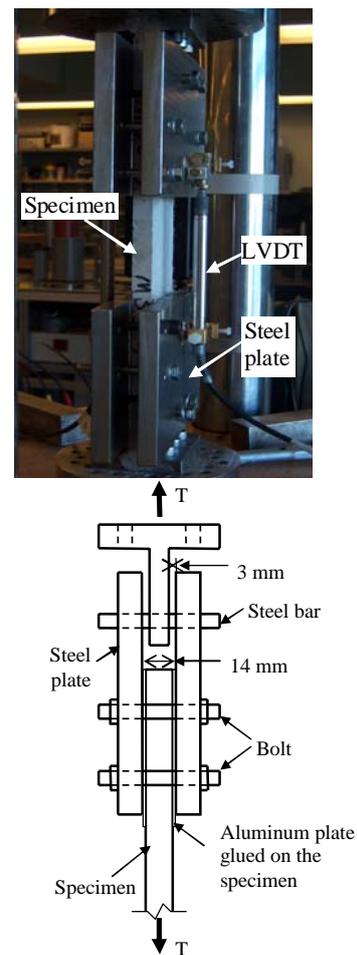

Figure 4. Uniaxial tensile test set-up.

4 VALIDATION OF THE PROPOSED METHOD

A set of equations has been developed based on parametric study of beam flexural model to correlate deflection and tensile strain capacity, as shown below, where Equations (1) and (2) can be used to calculate the average tensile strain capacity and its deviation, respectively. For more details about the derivation of the equations, readers are referred to Qian & Li (2007).

$$\varepsilon_{tu}^{'} = 0.50 \cdot \delta_u - 0.22 \qquad (1)$$

$$PD = 0.50 \cdot SD + 0.18 \qquad (2)$$

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 (%) considering the standard deviation of the deflection capacity, and SD is the standard deviation of the deflection capacity (mm). To be conservative, the lower bound equals to the lowest strain capacity value corresponding to $\delta_u - SD$. Likewise, the upper bound equals to the highest strain capacity value corresponding to $\delta_u + SD$. Therefore, the predicted deviation is the difference of upper bound/lower bound with predicted average tensile strain capacity.

It should be noted that this equation can only be applied to specimen with the same geometry and same loading conditions as that used by the first author. For the smaller size sample used by Zhou et al. (2009a), a new set of equations (3-4) has been developed to facilitate the transformation from deflection capacity to tensile strain capacity.

$$\varepsilon_{tu}^{'} = 0.77 \cdot \delta_u \qquad (3)$$

$$PD = 0.77 \cdot SD + 0.08 \qquad (4)$$

To validate the proposed inverse method, the deflection capacity obtained from FPBT is converted to tensile strain using Equations (1) and (2) and then compared with tensile strain capacity obtained directly from uniaxial tensile test for PVA-ECC 1-3. As revealed in Figure 5, the tensile strain capacity derived from FPBT predicts the uniaxial tensile test results with reasonable accuracy. This agreement demonstrates the validity of the proposed inverse method.
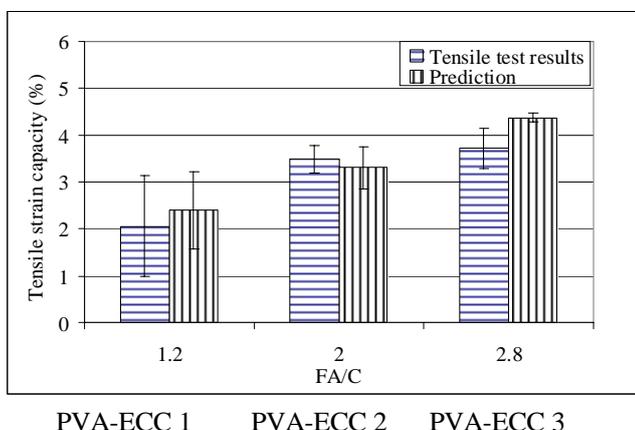

Figure 5. Comparison of tensile strain capacity from test and prediction.

To further verify the proposed inverse method, defection from M1-6 (Table 2) and MS1-6 (Zhou 2009b) was also converted to tensile strain capacity using Equations (3) and (4), which is derived based on the beam size as used in experiments of Zhou et al (2009a). As can be seen in Figures 6 & 7, the tensile test results generally agree well with predictions. It should be noted that M1-6 and MS1-6 were mixed by much smaller mixer (1.5 liter vs 12 liter) and tested with samples of much smaller size (120 mm × 30 mm × 10 mm vs. 356 mm x 76 mm x 50 mm). The general agreement between tensile test results and prediction suggest that the proposed inverse method is a valid method regardless of sample geometry.

It should be noted that MS5 and MS6 shows relatively large discrepancy between tensile test results and prediction. This may be explained by the higher robustness of bending test procedure in contrast with that of uniaxial tensile test procedure, where premature failure due to secondary flexure is unavoidable.
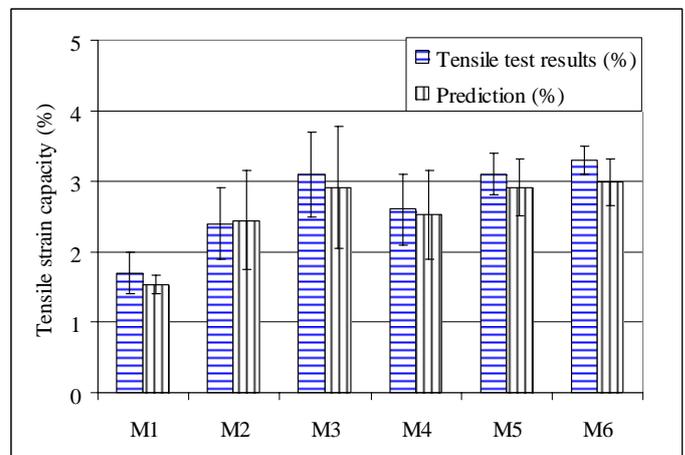

Figure 6. Comparison of tensile strain capacity from test and prediction (Zhou et al. 2009a).
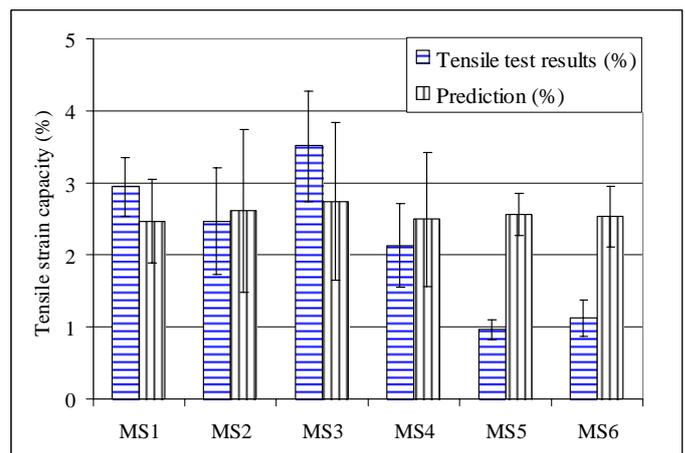

Figure 7. Comparison of tensile strain capacity from test and prediction (Zhou et al. 2009b).

5 CONCLUSIONS

To facilitate the quality control of the strain hardening cementitious composites on site, a simplified inverse method based on parametric study of beam

flexural model was proposed. This method converts the deflection capacity from simple beam bending test to tensile strain capacity through linear transformation. This proposed method has been extensively validated with uniaxial tensile test results from various sources. The wide range of SHCC mixtures, variation of geometry of sample and test setup suggests the versatility and robustness of this method.

ACKNOWLEDGEMENTS

PREFERENCES

Kanakubo, T. 2006. Tensile characteristics evaluation Method for DFRCC", Journal of Advanced Concrete Technology, 4 (1), 3-17.

Maalej, M. & Li, V.C. 1994. Flexural/Tensile Strength Ratio in Engineered Cementitious Composites, ASCE Journal of Materials in Civil Engineering, 6(4), 513-528.

Naaman, A. E. & Reinhardt, H. W. 1996. Characterization of High Performance Fiber Reinforced Cement Composites (HPFRCC), in High Performance Fiber Reinforced Cementitious Composites, RILEM Proceedings 31, Eds. A. E. Naaman and H. W. Reinhardt, 1-23.

Ostergaard, L., Walter, R. & Olesen, J. F. 2005. Method for Determination of Tensile Properties of Engineered Cementitious Composites (ECC), Proceedings of ConMat'05, Vancouver, Canada.

Qian, S. & Li, V. C. 2007. Simplified inverse method for determining the tensile strain capacity of SHCCs. Journal of Advanced Concrete Technology, 5(2), 235-246.

Qian, S. & Li, V. C. 2008. Simplified inverse method for determining the tensile properties of SHCCs. Journal of Advanced Concrete Technology, 6(2), 353-363.

Stang, H. & Li, V. C. 2004. Classification of Fiber Reinforced Cementitious Materials for Structural Applications, Proceedings of BEFIB, Varenna, Lake Como,Italy, 197-218.

Zhou, J., Qian, S., Guadalupe Sierra Beltran, M.G.M., Ye, G., van Breugel, K. & Li, V.C. 2009a. Development of engineered cementitious composites with limestone powder and blast furnace slag, Structures and Materials, in press.

Zhou, J. Qian, S., Ye, G., van Breugel, K. & Li, V.C.. 2009b. Processing sequence in the production of Engineered Cementitious Composites. ConMat'09, Nagoya, Japan, 24-26 August 2009.