A Simple Tensile Testing Method for UHP-FRC Based on Double-Punch Test

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Abstract:

Tensile properties are critical parameters of ultra-high-performance fiber-reinforced concrete (UHP-FRC). Current test methods such as the direct tensile test (DTT) and ASTM C1609 require a complicated test setup and large specimens. These tests are in general time consuming and typically produce test results with high variability between specimens. A simple, reliable, and reproducible test method in evaluating tensile properties of pre- and post-cracking of UHP-FRC is of paramount importance. In this regard, the double-punch test (DPT) can be a very suitable tensile testing method for the assessment of mixture quality and tensile behavior of UHP-FRC. The DPT is an indirect tensile test method, and it uses half of the conventional 152.4×304.8 mm (6×12 in.) concrete cylinder as test sample (that is, a 152.4×152.4 mm (6×6 in.) concrete cylinder). A compression is applied through two steel punches, having 25.4 mm (1 in.) height and 38.1 mm (1.5 in.) diameter, placed at the top and bottom surfaces of the cylinder along its central axis. The compressive load generates tensile stresses over diametric planes. A small capacity compression machine and a simple arrangement of LVDTs to measure the vertical deformation are the only test setup requirements, making the test procedure more efficient. The variability in DPT results is much smaller because, unlike the results of DTT and ASTM C1609, multiple cracked planes developed upon loading, thereby leading to an averaged mechanical behavior. This paper describes the DPT testing procedure and compares test results between DTT, ASTM C1609, and DPT. This paper also presents an approximate formula for estimating average and maximum crack width using axial deformation and does not require a circumferential extensometer.

Keywords: UHPC, UHP-FRC, double-punch test (DPT), tensile test, ASTM C1609, direct tensile test, crack width.

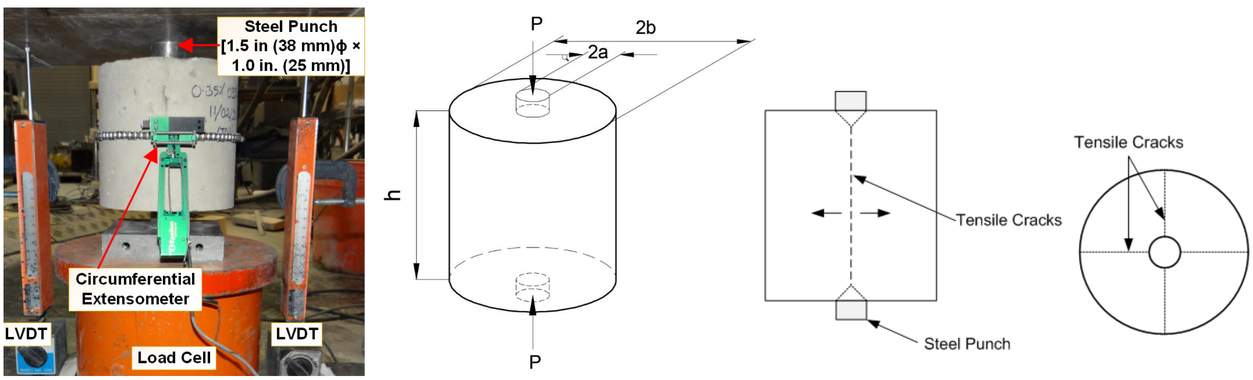
1. Introduction

The tensile properties of ultra-high-performance fiber-reinforced concrete (UHP-FRC) are important parameters for understanding its behavior such as peak strength, post-cracking ductility, and residual strength. These tensile properties can also be utilized in analysis and design of UHP-FRC structural members. Therefore, it is essential that a material testing can provide consistent and reliable results of the pre-cracking and post-cracking tensile properties of UHP-FRC.

Current test methods such as the uniaxial direct tensile test (DTT) and ASTM C1609 (ASTM, 2012) require a complicated test setup and large specimens. DTT usually has a complicated test setup. The major drawback of DTT is the inconsistency in the location and orientation of percolation cracks which cause a high variability in the peak strength and post-cracking responses. It is also challenging to eliminate eccentricity between the center of the specimen and the line of load action, as well as any induced bending moment after a crack initiates. Often, the critical crack can develop outside of the gauge length due to high stress concentration near the grip at the specimen ends. The critical crack usually occurs along the weakest path, which can be largely affected by local fiber distribution. In ASTM C1609 test, similarly, failure of the specimen is typically dominated by a single large crack, which can be largely affected by the extent of fiber distribution at the crack plane. The within-batch coefficient of variation (COV) of responses from the ASTM C1609 test has been reported from 15% to greater than 20% (Chao et. al., 2011). Despite the considerable improvements that have been made in ASTM C1609 over the years, this testing procedure still presents major difficulties in accurately describing the behavior of fiber-reinforced concrete (FRC). Hence, it is essential to have an alternative tensile test method that is simple and reliable. In this regard, the double-punch test (DPT) can be an excellent candidate. Molins et al. (2009) compared experimental results between the DPT and beam test with various types and different amounts of fiber content. They concluded that the DPT provided more consistent results because the coefficient of variation (COV) for the peak and residual strengths were smaller than those from the beam test. Chao et al. (2012) compared the ASTM C1609 test, DTT, and DPT, and they observed that DPT consistently exhibits low variability along the entire load-versus-deformation curves. They indicated that DPT can distinguish between specimens with different FRC mixtures, in terms of strain-hardening or strain-softening, ductility, residual strength, and toughness. This study investigates the applicability of using DPT for UHP-FRC and compares the results with those obtained by the DTT and ASTM C1609 bending test.

2. Double Punch Test (DPT)

DPT is an indirect tensile test method for evaluating the tensile properties of plain concrete and FRC (Chen, 1970; Chen and Yuan, 1980). Its foundation is the theory of plasticity. This method uses a half size conventional 152.4 × 304.8 mm (6×12 in.) concrete cylinder as the test sample (that is, a 152.4×152.4 mm (6×6 in.) concrete cylinder). A compression is applied through two steel punches, having 25.4 mm (1 in.) height and 38.1 mm (1.5 in.) diameter, placed at the top and bottom surfaces of the cylinder along its central axis as shown in Figures 1a and 1b. The compressive load generates tensile stresses over diametric planes on the cylindrical specimen. Figure 1c shows the failure pattern consisting of the conical wedge formed beneath each punch and vertical tensile crack. DPT specimens typically develop multiple crack planes under an applied load as shown in Figure 1d. These multiple crack planes have a large cracked area which gives an average mechanical behavior to minimize the influence of fiber distribution on a single critical crack plane that occurs in both the DTT and ASTM C1609 bending test. The top and bottom surfaces are smoothened with sandstone or by grinding so that steel punches make uniform contact with the top and bottom faces of the specimen. The centering of the punch is critical to avoid eccentric loading. It is suggested that the centroid of each steel punch should align with the centroid of the cylinder surface within ± 2.5 mm (± 0.1 in). To fully seat punches and minimize possible unevenness of specimen surfaces, it is suggested that a "shakedown" is carried out in which the specimen is first loaded at a rate of 1.0 mm/min (0.04 in./min) up to a load of approximately 8.9 kN (2 kips) then unload the specimen at a 0.1 mm/min rate (0.04 in./min) to a load of 2.2 kN (0.5 kips). Then, reload the specimen at the rate of 1 mm/min (0.04 in./min) up to an ultimate deformation of 7.6 mm (0.3 in.). More details regarding the testing procedure can be found in a draft ASTM standard for DPT (ASTM, 2019). Following the procedure one test can typically be completed within 12-15 minutes. For DPT, a small capacity closed-loop servo-controlled compression machine and a pair of linear variable differential transformers (LVDTs) to measure the vertical deformation are the only test setup requirements. A circumferential extensometer is not needed but is optional when accurate circumferential strain and crack width are needed.



(a) **(b)** **(c)** **(d)**

Figure 1. (a) DPT setup (circumferential extensometer is optional), (b) DPT arrangement, (c) tensile cracks occur along these diametric planes, and (d) cracks occur in multiple planes and give averaged tensile strength

The formula, Equation (1), for computing the tensile strength in a DPT specimen is obtained from the from plasticity analysis for concrete and modified based on experimental testing by Chen and Yuan (1970). Equation (1) is valid for $b/a \le 4$ or $h/2a \le 4$. For any ratio $b/a > 4$ or $h/2a > 4$, the limiting value $b = 4a$ or $h = 8a$ should be used in Equation (1) for determination of tensile strength.

$$f_t = \frac{0.75 \times P}{\pi(1.2bh - a^2)} \tag{1a}$$

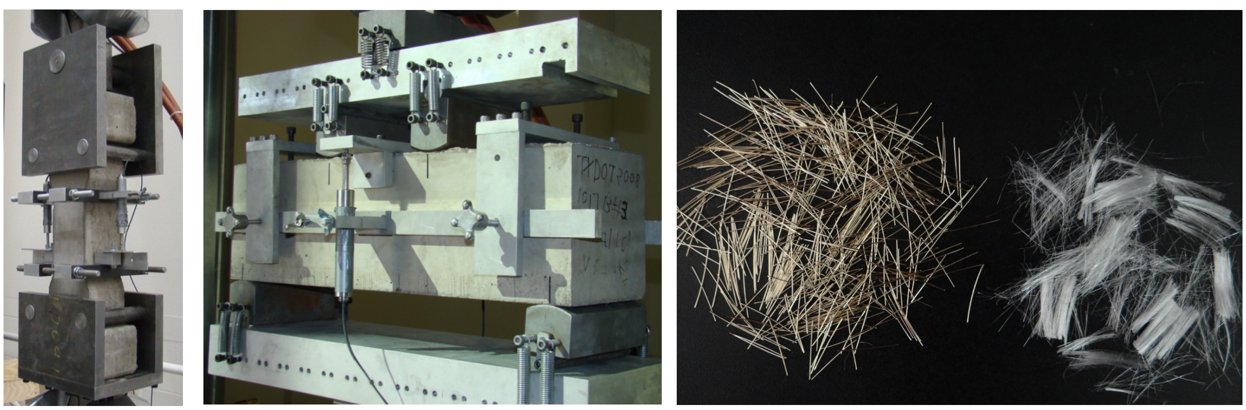
where f_t is equivalent tensile stress, P is applied load (lbs or N), b is radius of the cylinder at 76.2 mm (3 in.); h is height of cylinder at 152.4 mm (6 in.), and a is the radius of punches = 19 mm (0.75 in.) (Figure 1a). Equation (1) can be further simplified as:

$$f_t = 0.0113P \text{ (psi)}, P \text{ in lbs} \tag{1b}$$
or
$$f_t = 0.000176P \text{ (MPa or N/mm}^2\text{)}, P \text{ in N}$$

3. Experimental Program

The scopes of this experiment were: (1) to assess the suitability of the DPT method for UHP-FRC material in providing a reliable test data with smaller variability, (2) to determine tensile strength and behavior in both the pre- and post-cracking stage, (3) to compare DPT with DTT and the ASTM C1609 beam test, and (4) to derive a simple formula to estimate the average and maximum crack widths, which allows a convenient estimation when a circumferential extensometer is not available. For DTT (Figure 2a), the dog-bone-shaped specimen has a square cross-sectional area of 101.6 mm×101.6 mm (4 in.×4 in.). This dimension was selected to ensure more uniformly distributed fibers while maintaining a suitable weight for laboratory handling (Chao et. al., 2011). The ASTM C1609 beam test (Figure 2b) is a standard test used to evaluate the flexural performance of FRC by using parameters derived from a load-deflection curve obtained by testing a simply supported beam under third-point loading. Its specimen has a prism shape with a dimension of 152.4×152.4×508 mm (6×6×20 in.). Both tests were carried out by a closed-loop, servo-controlled machine with a loading rate of approximately (0.05 mm/min) (0.002 in./min).

Two types of fibers: micro short steel fibers and ultra-high-molecular-weight polyethylene (PE) fibers were used in two different UHP-FRC mixes. The properties of these two fibers are listed in Table 1. Furthermore, 3% micro-short steel fiber and 0.75% polyethylene (PE) fiber were used in the experiments. The UHP-FRC mixture was developed based on the dense particle packing concept (Aghdasi et al., 2016).



(a) (b) (c)

Figure 2. (a) Direct tensile test (DTT) setup, (b) ASTM C1609 test setup, (c) micro steel fibers (left) and ultra-high-molecular-weight polyethylene fibers (right)

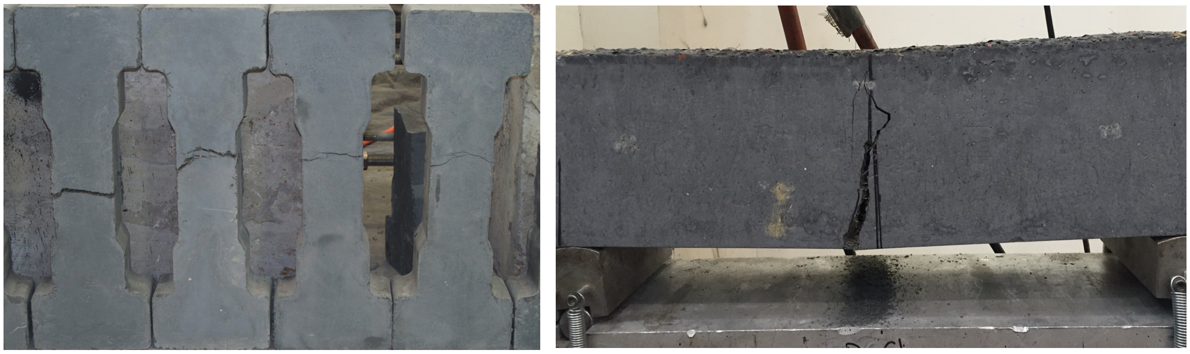
Table 1. Properties of the fibers used in this study

	Length mm (in.)	Diameter mm (in.)	Tensile strength MPa (ksi)
Micro steel fiber	13 (0.5)	0.20 (0.0079)	2158 (313)
UHMW Polyethylene fiber	13 (0.5)	0.0015 (0.00006)	2586 (375)

4. Experimental Results

4.1. Comparison between DTT, ASTM C1609 test, and DPT

Based on the compressive tests obtained using a 70.6 mm (2.78 in.) cube, UHP-FRC with steel fibers had a higher 28-day compressive strength (152 MPs or 22 ksi) than UHP-FRC with PE fibers (124 MPs or 18 ksi). Crack patterns in specimens of DTT and ASTM C1609 beam tests are shown in Figure 3. As can be seen, the failure in DTT and ASTM C1609 test is typically governed by a single critical crack surface. On the other hand, multiple crack surfaces developed in DPT specimens as shown in Figure 4. Notably, Figure 4 shows that while the crack paths are irregular in UHP-FRC with steel fibers, the crack paths are quire smooth in UHP-FRC with PE fibers.



(a) **(b)**

Figure 3. Crack patterns in specimens of (a) DTT and (b) the ASTM C1609 test

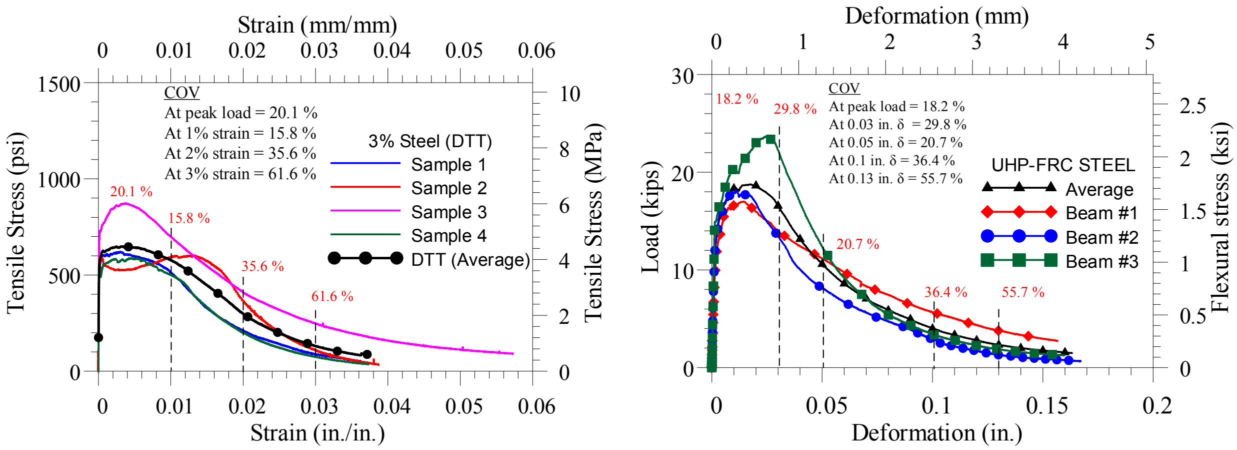
(a) **(b)** **(c)**

Figure 4. Crack patterns in DPT specimens (a) UHP-FRC with steel fibers, (b) UHP-FRC with PE fibers, and (c) UHPC (0% fibers)

Test results for specimens of DTT, the ASTM C1609 bending test, and the DPT are presented in Figure 5 and Figure 6, respectively. COVs at various strains or deformations are also shown in these figures and in Table 2. In general, the COVs of peak strength and post-cracking strengths throughout the curves of DTT and ASTM C1609 bending test are much higher than that of DPT. The DPT results show low variability in which each individual curve is close to the average one. Figure 6 also shows that DPT can show strain-hardening and ductility of UHP-FRC. Prior research (Chao et al., 2012) has consistently observed that the bottom halves of the DPT specimens with conventional FRC mixtures give less variability and slightly higher peak strength than that of the top halves of the cylinders. This trend was also observed for UHP-FRC. Comparing Figures 6 and 7, it can be seen that the bottom halves have less COVs and higher peak strengths than that of the top ones. Therefore, only the bottom halves of the DPT specimens are recommended for evaluation purposes.

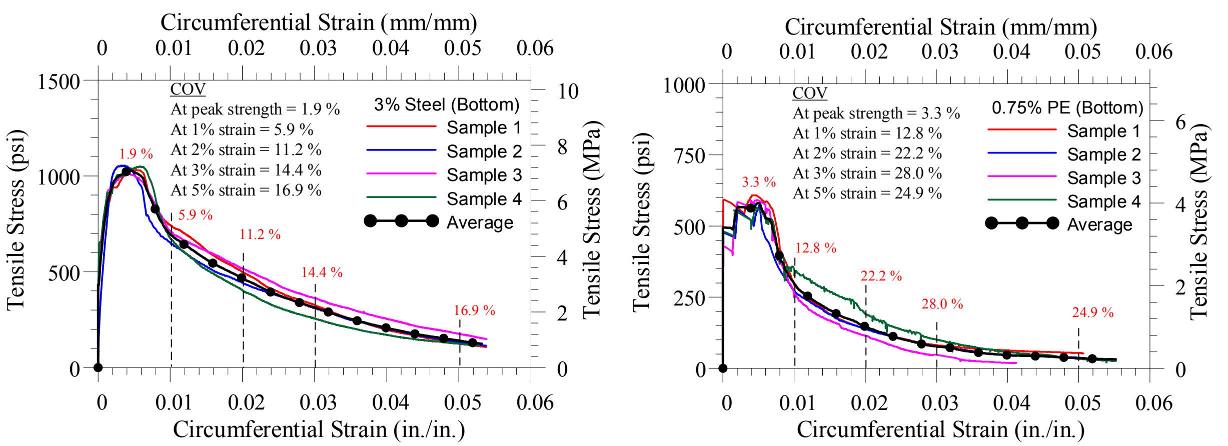
Table 2. COVs obtained from different test methods

Test Method	**Fiber Type**	**At Peak**	**At 1% strain**	**At 2% strain**	**At 3% strain**
Double-punch test (bottom halves)	UHP-FRC (Steel)	1.9 %	5.9 %	11.2 %	14.4 %
	UHP-FRC (PE)	3.3 %	12.8 %	22.2 %	28.0 %
Direct tensile test	UHP-FRC (Steel)	20.1 %	15.8 %	35.6 %	61.6 %
		At Peak	**At 0.03 in. δ**	**At 0.03 in. δ**	**At 0.03 in. δ**
ASTM C1609 test	UHP-FRC (Steel)	18.2 %	29.8 %	20.7 %	36.4 %5



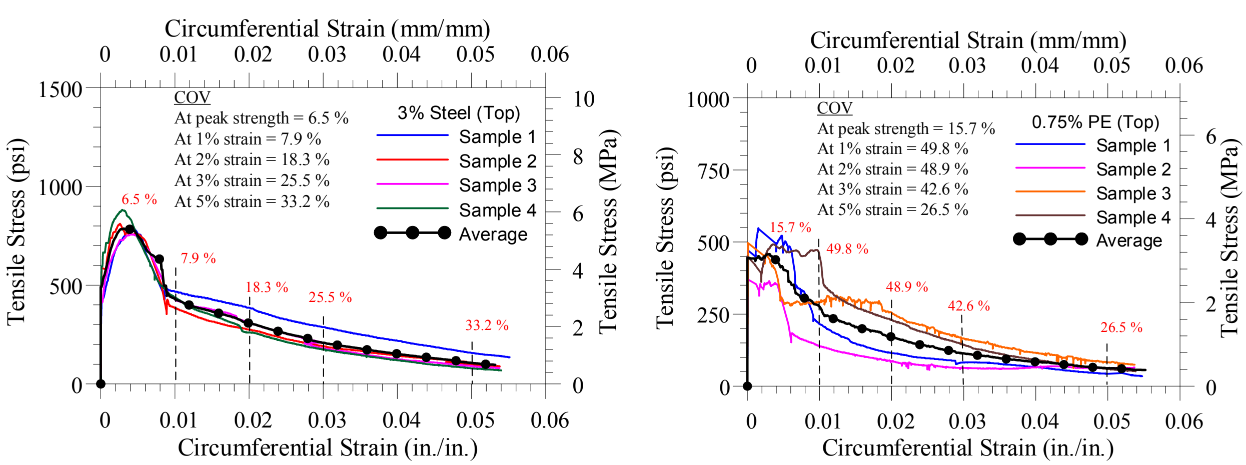
(a) **(b)**

Figure 5. UHP-FRC specimens with steel fibers: (a) DTT and (b) ASTM C1609 test



(a) **(b)**

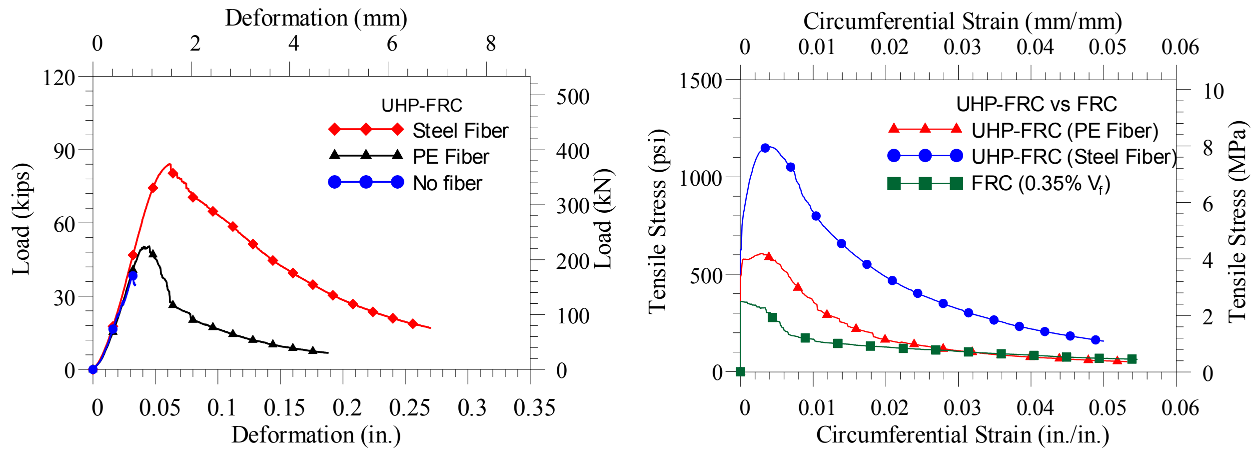
Figure 6. DPT test results (bottom halves): (a) UHP-FRC with steel fibers and (b) UHP-FRC with PE fibers



(a) **(b)**

Figure 7. DPT test results (top halves): (a) UHP-FRC with steel fibers and (b) UHP-FRC with PE fibers

Figure 8a shows that DPT can clearly identify the responses of different UHP-FRC and UHPC (no fibers) mixtures. While the three mixtures have similar initial stiffness in the elastic region, the peak load and ductility of UHP-FRC with steel fiber is highest among all three. A six-sample set of regular FRC with 0.5% fiber volume fraction was selected to compare with the DPT results of UHP-FRC. Figure 8b indicates that DPT can distinguish tensile strain-hardening and strain-softening behavior, as well as residual strengths of different categories of FRC.

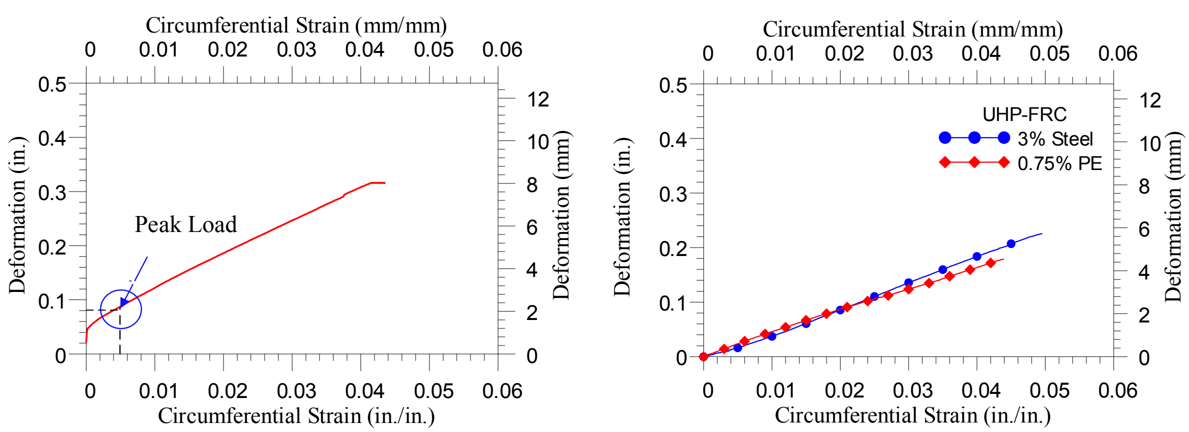


(a) **(b)**

Figure 8. Features of DPT responses: (a) Load versus deformation responses with various UHP-FRC mixtures (b) tensile stress versus circumferential strain responses with different FRC mixtures

4.2. Relation between deformations and circumferential strains of DPT response

The first cracking typically starts before the peak load (or peak tensile strength) but its width remains small. The crack opening becomes more noticeable and increases at a faster rate after the peak load. Circumferential elongation abruptly increases at a vertical axial deformation of 1 mm (0.04 in.) and maintains an approximately constant rate up to the end of testing. Since crack width after peak strength is of interest to the engineering community, only the vertical deformation measured by the LVDTs and the circumferential strain after the peak load is considered for determining their relationship in these experiments. Figure 9 indicates that the relationship between vertical deformation and circumferential strain is very close to a linear relationship.



(a) **(b)**

Figure 9. (a) Total vertical deformation vs. circumferential strain of DPT specimens and (b) post-peak vertical deformation vs. circumferential strain of DPT specimens

Therefore, the slope (α) was determined by means of a linear regression using all data obtained from this experimental program. Average α was found to be between 4.1 to 4.2 and can be conservatively taken as 4.0.

$$\delta_P = \alpha\varepsilon_P \qquad \text{where, } \alpha = 4 \quad \text{for UHP-FRC} \tag{2}$$
$$\delta_P = \delta - \delta_0$$

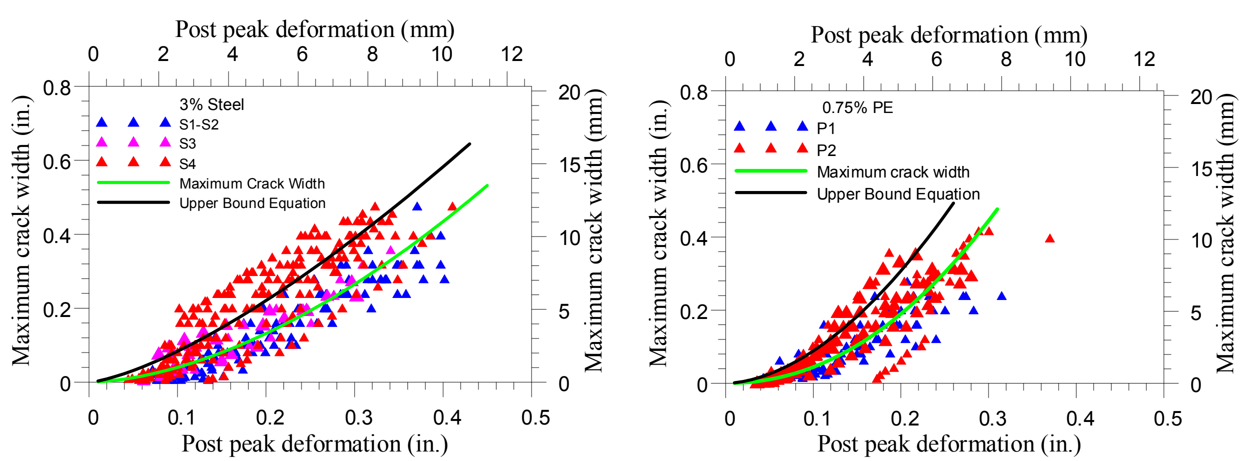
where δ_0 is the average deformation at the peak load measured by LVDTs; δ is the average total vertical deformation from the beginning of the test; δ_P is the post-peak deformation, and ε_P is the circumferential strain after peak force measured by a circumferential extensometer.

4.3. Approximation equations for determining the average and maximum crack width

Experimental results indicate that no circumferential strain was measured before the peak load, the initial perimeter (πD_0) is assumed to be the perimeter at the peak and ε_P (circumferential strain at peak) is considered the same as ε. Average crack width (CW_{Ave}) in a specimen is determined by dividing the total measured crack width by the number of cracks (N). The number of cracks is determined by visual inspection after the test. The number of cracks was counted at the end of the experiment as it is difficult to count the number of cracks while the testing is in progress. Figure 4 shows that N can be taken as 2 for UHP-FRC with steel fiber, and it is in the range of 4 to 9 for UHP-FRC with PE fiber. A somewhat average number of 5 was used for UHP-FRC with PE fiber as about 35% of the specimen had five cracks. UHPC with no fibers suddenly cracked and failed in about 4 pieces once a specimen reached the peak load. Only cracks that started radially from the center and propagated at least up to the mid-height of the specimen were considered. The very small minor cracks are considered as having less effect on the residual stress. The crack width in DPT can be found using Equation (3). Use Eq. (2): $\delta_P = \alpha\varepsilon_P$,

$$CW_{Ave} = \left(\pi D_0 \times \delta_P\right) / \alpha N \tag{3}$$

Unlike the average crack width, the maximum crack width does not show a linear relation with the deformation, δ. This nonlinear relation is shown in Figure 10.



(a) UHP-FRC with steel fibers **(b) UHP-FRC with PE fibers**

Figure 10. Maximum crack width versus post-peak vertical deformation in DPT specimen with UHP-FRC

A nonlinear relation between the maximum crack width and δ was developed based on the available data. The measured maximum crack widths during and at the end of tests were compared with the predicted maximum crack width. The relationship between deformation and the predicted maximum crack width using a nonlinear regression, is in the form of

$$\delta_P = \lambda CW_{max}{}^{\beta} \tag{4}$$

where, δ_P is post peak deformation, β is a factor and CW_{max} is predicted maximum crack width. The above equation is shown as Table 3 representing the approximate median value of the measured maximum crack widths (black color curves in Figure 10). Conservatively, an upper bound CW_{max} (green color curves in Figure 10) can also be estimated by using the equations in Table 3.

Table 3. Predicted median and upper bound maximum crack widths of UHP-FRC DPT specimens

Units	Median Value		Upper bound value		δ_P and CW_{max} (Units)
	UHP-FRC (steel)	UHP-FRC (PE)	UHP-FRC (steel)	UHP-FRC (PE)	
U.S	$CW_{\max} = 2.1\delta_P^{1.72}$	$CW_{\max} = 5.57\delta_P^{2.1}$	$CW_{\max} = 2.1\delta_P^{1.4}$	$CW_{\max} = 5.57\delta_P^{1.8}$	inch
S.I	$CW_{\max} = 0.19\delta_P^{1.72}$	$CW_{\max} = 0.15\delta_P^{2.1}$	$CW_{\max} = 0.57\delta_P^{1.4}$	$CW_{\max} = 0.41\delta_P^{1.8}$	mm

5. Conclusions

This paper introduces a potential standard material testing method for ultra-high-performance fiber-reinforced concrete (UHP-FRC) – double-punch test (DPT). DPT is a simple and reliable test method for determining the tensile strength and for evaluating the post-peak behavior of UHP-FRC. The test results obtained from DPT represent an averaged mechanical behavior as the multiple crack planes occur simultaneously. Therefore, the load-versus-deformation curves or tensile stress-versus-circumferential strain curves show smaller variations for specimens cast in the same batch. This feature allows DPT to also serve as a method for mixture quality evaluation. Conversely, in both the uniaxial direct tensile test (DTT) and ASTM C1609 third-point bending test, the performance is usually governed by one major crack, which can be largely affected by the extent of fiber distribution. Consequently, the test data shows very high variability for specimens cast in the same batch. DPT can distinguish the behavior between different UHP-FRC mixtures with different types fibers, matrix strengths, and fiber volume fraction. Responses from DPT can provide key features of the UHP-FRC mixtures such as strain-hardening, strain-softening, and post-cracking ductility. DPT can also evaluate and compare the performance of UHP-FRC mixtures from the nature of the cracks (number and crack width). A linear correlation was found between post-peak vertical deformation measured by LVDTs and the circumferential strain. Formulas were derived to estimate the average crack width and maximum crack width at the specified post-peak vertical deformation of DPT samples. This allows the estimation of crack widths in DPT specimens by only use LVDTs without using a circumferential extensometer or making measurements during testing.

6. References

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7. Acknowledgements

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