Effects of Size and Gauge length on the Stress-Strain Response of UHPC in Tension

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Abstract:

The use of UHPC continues to grow rapidly and a great deal of present-day research focuses on understanding and fine tuning of this material composition. This work is aimed at understanding the effects of size on the tensile behavior of UHPC in relation to the fiber percentage. The paper also discusses the variation in the stress-strain responses based on the chosen gauge length for the tension characterization. Several UHPC dog bone shaped specimens have been tested in the laboratory under the displacement controlled mode. The size effect is assessed by comparing the results of the specimens with cross sections of 2 in. x 2 in., 2 in. x 4 in., and 4 in. x 4 in. The response of the specimens was measured with LVDT and a 3D optical tracking system. The LEDs for the optical tracking measurements were placed at 1 in. interval over a length of 14 in. in the critical zone of the specimen where failure was anticipated. The results show that the effect of size on the stress-strain curves is not consistent between different fiber ratios and there is noticeable variation in the formation of micro cracking along the member length. The chosen gauge length for the measurement of the stress-strain curves can have significant effect on the peak and ultimate strain values. Larger gauge lengths can include micro-cracks over a longer length, averaging the micro-crack behavior more accurately. However, they can have significantly lower peak strain and post-peak behavior when compared with a smaller gauge length.

Keywords: UHPC, tension test, gauge length, size effect, micro-crack distribution.

1. Introduction

Ultra High Performance Concrete (UHPC) is a versatile material with superior properties when compared with the regular concrete. UHPC exhibits greater strength, ductility, durability, and has better service life performance. Developed for commercial application in the late 90's, its usage has grown from research to largescale commercial constructions. According to the structural definition given by the ACI 239R (ACI 239R, 2018), "ultra-high-performance concrete is a concrete that has a minimum specified compressive strength of 150 MPa (22,000 psi) with specified durability, tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements". There are several proprietary and non-proprietary mixes available in the market which meet this definition of UHPC. The reported tensile strength of UHPC with 2% steel fiber content is typically in the range of 0.87 ksi to 1.3 ksi (6-9 MPa) (Aaleti, 2013) and, values as high as up to 2.61 ksi (18 MPa) have been reported (Park et al, 2012). The percentage of the fibers greatly affects the tensile properties like peak strength, peak strain, strain hardening and ductility.

The reported tensile strengths of UHPCs are based on the test results using the specimen length of different sizes for testing and somewhat arbitrarily chosen gauge length for the measurement of strain, although 4 in. has been more frequently used. It is well known that the mechanical properties of concrete are size dependent (Bažant, 1999) and these test results cannot be used for practical purposes or in design, unless the effect of size on the tensile strength is completely understood. Fibers play an important role in the tensile behavior of UHPC and the size effect on the tensile properties of UHPC in relation to the fiber content needs be understood well before adopting a suitable tensile stress-strain curves in design and analyses. Due to the presence of fibers, UHPC experiences micro-cracking in the non-linear phase of the stress-strain curve i.e. after the elastic zone and before the formation of local crack. Its distribution may not be uniform along the length of the specimen and the gauge length that is used to quantify the behavior may provide a different result than the actual response. Larger gauge lengths will include micro-cracks over a longer length, potentially averaging the micro-crack behavior, and provide significantly lower peak strain and ultimate strain values when compared to the corresponding values established with a smaller gauge length. Accurate stress-strain curves are necessary for the cost-effective and safe design of the elements made out of UHPC.

2. Background

There are several studies available in the literature, which confirm the size effect in regular and high strength concrete (Bažant and Schell, 1997; Kim and Yi, 2002; Karihaloo et al., 2003; Tokyay and Ozdemir, 1997; Krauthammer et al., 2003; Sener, 1997). Tokyay and Ozdemir (1997) investigated the size effect on high strength concrete in compression by performing tests on different sized cylinders having constant length-to-diameter ratio (l/d), different sized cubes, and also on cylinders with various l/d. They concluded that the larger specimens had lower strength. Sener (1997) also suggest that the nominal compressive strength at failure decreases as the specimen size increases. Krauthammer et al. (2003) confirmed these effects in high strength concrete and noted that the rate of loading also plays an important role in the strength and, the inter-relation between size and rate of loading should be clearly understood. Kim and Yi (2002) worked on the size effect in the beams made out of high strength concrete and concluded that the flexural compressive strength at failure decreases as the specimen size increases.

Several studies have also focused on the size effect in UHPC in compression and flexure (Phillip and Torsten, 2017; Yoo et al., 2016; Paschalis and Lampropoulos, 2015; Nguyen et al., 2013). Phillip and Torsten (2017) tested cubes and cylinders of different sizes made with normal strength concrete (NSC), high strength concrete (HSC), and UHPC. The cube size varied between 4 to 6 in. (100 and 150 mm) and the cylinder diameter varied between 4 in. to 6 in. (100 mm and 150 mm) with a constant l/d ratio of 2. The maximum grain size in UHPC varied from 0.5 mm to 8 mm (0.02 to 0.3 in.). It was observed that for UHPC, the ratio of compressive strength between cylinder and cube is close to 1. It was also noted that compared with NSC and HSC, the effect of specimen size and slenderness on the compressive strength is very small for UHPC. Yoo et al. (2016), Paschalis and Lampropoulos (2015) and several other researchers have examined the size effect in UHPC beams. All the studies concluded that the strength of UHPC beams decreased with increase in the cross section of the beams. Yoo et al. (2016) concluded that the decrease in the capacity is due to different fiber distribution characteristics and that the size effect can be minimized by altering the fiber distribution. Nguyen et al. (2014) evaluated the size effect of UHPC in tension and concluded that the different sizes and geometries of specimens did not generate any significant influence on the post cracking strength of UHPC but produced clear effects on the strain capacity, energy absorption capacity, and cracking behavior of UHPC. However, the study did not focus on the effect of fiber ratio on the size effect. At present there are no studies available which document the size effect in relation to fiber content. Nguyen et al. (2014) evaluated the effect of gauge length on the stress-strain curves of UHPC by casting dog bone shaped specimens with different lengths. They concluded that as the gauge length is increased, the peak strain values would decrease and the number of cracks and crack spacing would increase. Even though cast from same mix, different specimens will have different fiber distribution and it is well known that the fiber distribution greatly affects the tensile response and crack formation in UHPC. Comparison of results from different specimens will not capture the effect of gauge length accurately and this issue should be addressed to accurately conclude the effect of gauge length. The specific objectives of the study are to: 1) evaluate the size effect in UHPC in relation to different fiber ratios; and 2) investigate the influence of gauge length on the strain limits, crack distribution and energy absorption without casting different specimens.

3. Experimental Program

3.1. Materials and Casting of Specimens

The UHPC required for the casting of specimens was procured from the market from different vendors although results are presented for one supplier. This UHPC is sold as a premix which should be mixed with fibers, water and superplasticizer as per the mix design. The mix design for this study is shown in Table 1. The steel fibers are added to the mix after adding the water and superplasticizer. The properties of steel fibers are given in Table 2.

Table 1. Mix design

UHPC	lbs. per yd3
Premix	3700
Water	202
Superplasticizer	51
Steel Fiber (1% or 2%)	131 or 262

Note: (1 lb = 0.45 kg and 1 yd^3 = 0.7645 m^3)

Table 2. Properties of steel fibers

Fiber material	Length (in.)	Diameter (in.)	Tensile strength (ksi)	Elastic Modulus (ksi)
Steel	0.5	0.00787	399	29000

Note: (1 in. = 25.4 mm; 1ksi = 6.89 MPa)

When casting a full scale structural member with UHPC, the orientation of fibers is expected to be random and it is impossible to achieve the same randomness in the laboratory due to the limited size of the test specimens. For this reason, a casting method which allows fibers to align primarily in one direction was chosen to ensure consistency between the test samples. This will eliminate the variation in the fiber distribution as the probable cause for any observed effects in the test results. The chosen casting procedure for specimens involved pouring UHPC into the molds which are placed with a slight inclination with respect to the floor, allowing the UHPC to flow from one end of the mold to the other end. This casting procedure allowed fibers to primarily align longitudinally within the specimen, along to the direction of flow. After the molds are filled with UHPC, they are placed on horizontal surface and the top layer of UHPC is levelled.

3.2. Specimen Details and Data Acquisition

The dog bone shape was chosen to perform the tests. The specimens are 36 in. (914.4 mm) long with a 10 in. (254 mm) long narrow zone at the middle of the specimen (see Figure 1). The cross section in this portion is varied between 2 in. x 2 in., 2 in. x 4 in. and 4 in. x 4 in. (50.8 mm x 50.8 mm, 50.8 mm x 101.6 mm and 101.6 mm x 101.6 mm respectively). This variation allowed sufficient evaluation of size effect. The transition from the narrow zone to the wide gripping zone was achieved by increasing the width following a circular curve of radius 2 in. (50.8 mm). In total nine specimens were tested to achieve the set objectives. The test series is shown in Table 3.

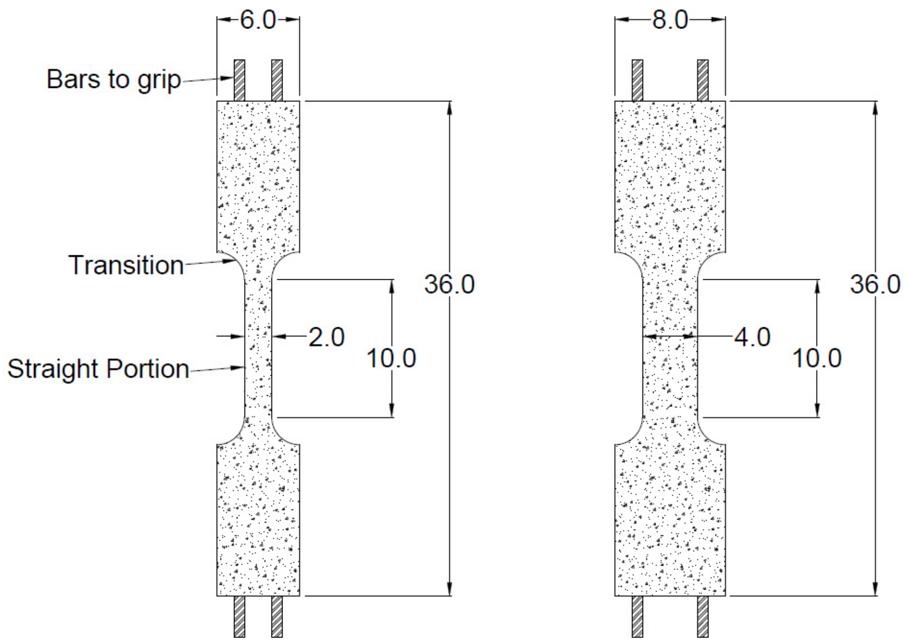


Figure 1. Specimen details (Dimensions in inches; 1 in. = 25.4 mm)

A linear variable displacement transducer (LVDT) was attached to the specimen on the back side to capture the overall deflection of the specimen. Micro-crack and local crack information was captured using the NDI Optotrak LED system. In this case, LEDs were attached to the specimen at 1 in. (25.4 mm) interval, along two vertical lines (see Figure 2). Each LED had initial coordinates in an x-y-z space, which were tracked during testing via an Optotrak Certus HD camera. Data collected from these LEDs were used to determine the total displacements and strains at different gauge lengths. This assisted with evaluating the effect of gauge length from a single specimen. The load and displacement data from the MTS tensile testing unit were collected in synchronization with the LED data.

Table 3. Test series

Specimen Name	Dimension at mid-section (w x h) (in. x in.)	Fiber content (%)
S1-22-0	2x2	
S1-24-0	2x4	0
S1-44-0	4x4	
S1-22-1	2x2	
S1-24-1	2x4	1
S1-44-1	4x4	
S1-22-2	2x2	
S1-24-2	2x4	2
S1-44-2	4x4	

Note: (1 in. = 25.4 mm)

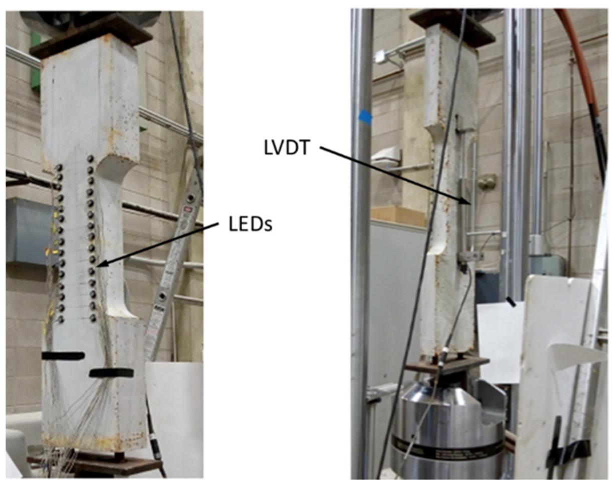


Figure 2. LED layout and LVDT position

3.3. Test Setup and Procedure

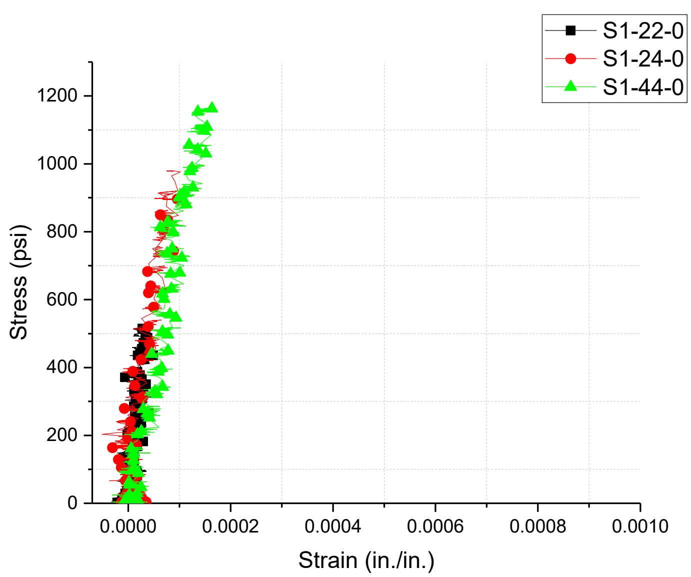
Direct tensile tests were conducted on the dog bone shaped specimens using a MTS uni-axial tensile test machine. The specimens were loaded in displacement control mode until failure. Specimens with fibers were subjected to a three-part displacement controlled loading procedure as follows: 0.05 in./min (1.25 mm/min) until 0.1 in. (2.5 mm) of deformation; 0.03 in./min (0.75 mm/min) until 0.2 in. (5 mm) of total deformation; and 0.1 in./min (2.5 mm/min) until failure. The primary goal of this loading procedure is to make the three regions of the stress-strain curve, viz., the elastic, nonlinear, and post-peak phases, occur over approximately equal time intervals for specimens with fibers. Specimens without fibers were loaded at 0.05 in./min (1.25 mm/min) until failure. Specimens were cast with threaded bars at the ends which were anchored to T-shaped steel plates using nuts. These T-shaped steel plates were then gripped by the MTS tensile testing unit.

4. Test Results And Discussion

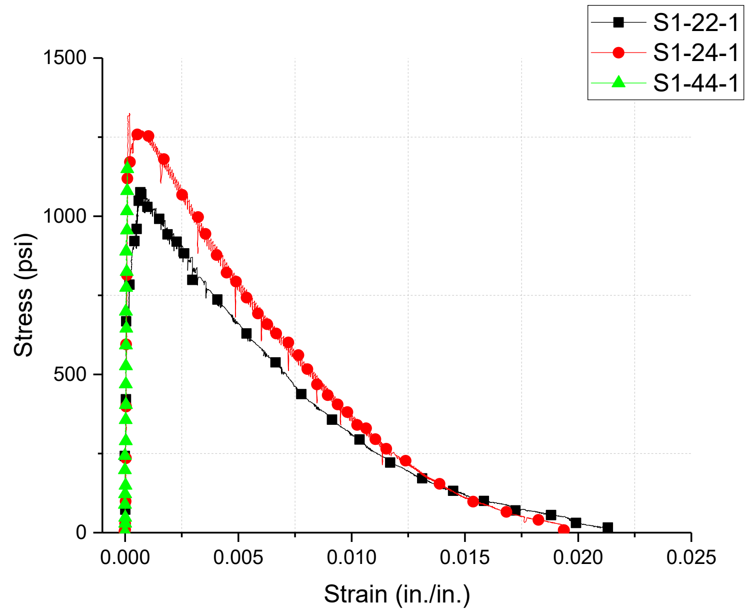
The data collected from the tests were analyzed to quantify the effect of size and gauge length. The stress values were calculated by dividing the recorded load with the cross sectional area of the specimen and the strains were calculated by dividing the deformation between two referenced LED points by the initial distance between them. In this study, the following gauge lengths were chosen: 14 in. (355.6 mm), 8 in. (203.2 mm), 4 in. (101.6 mm), 2 in. (50.8 mm), and 1 in. (25.4 mm). When identifying the region for each gauge, it was ensured that the local crack would be in the middle of the selected gauge length.

4.1. Size Effect

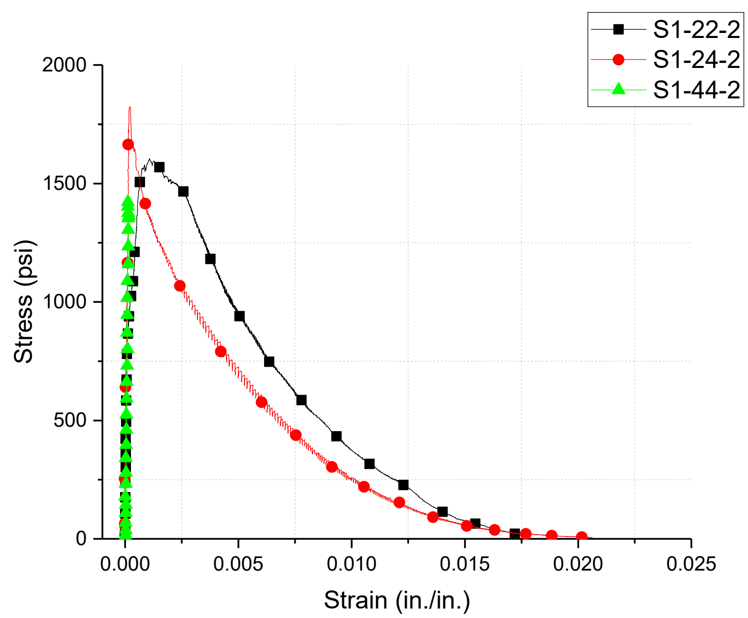
The effect of size was evaluated by comparing the stress vs strain curves of the specimens with different sizes. Figure 3a shows the stress-strain curves of the specimens without any fibers. It was observed that as the specimen size was increased from 2 in. x 2 in. (50.8 mm x 50.8 mm) to 2 in. x 4 in. (50.8 mm x 101.6 mm) to 4 in. x 4 in. (101.6 mm x 101.6 mm), the peak stress increased from 523 psi to 980 psi to 1164 psi (see Table 4). For specimens with 1% fibers the variation was from 1088 psi to 1325 psi to 1184 psi for 2 in. x 2 in. (50.8 mm x 50.8 mm) to 2 in. x 4 in. (50.8 mm x 101.6 mm) to 4 in. x 4 in. (101.6 mm x 101.6 mm) specimens respectively. This trend is not similar to the one without fibers, indicating no consistent influence of size effect. The stress increased from 2 in. x 2 in. (50.8 mm x 50.8 mm) to 2 in. x 4 in. (50.8 mm x 101.6 mm) but decreased from 2 in. x 4 in. (50.8 mm x 101.6 mm) to 4 in. x 4 in. (101.6 mm x 101.6 mm) specimen. Similar trend was observed for specimens with 2% fibers (see Table 4). It was observed that for 4 in. x 4 in. (101.6 mm x 101.6 mm) specimens with fibers, the stress-strain curves had negative strain values after the peak load and, these values are not shown in the plot and only the elastic part of the stress-strain curves is shown in Figures 3b and 3c. This is due to the out of plane bending of the specimen that became an issue at the onsite of localized crack formation. This crack originated on the back side of the specimen, leading to a partial hinge like action (see Figure 4) increasing the strain on the back side of the specimen and prematurely pulling the fibers on this side. This reduced the peak stress values and eliminated the strain hardening portion of the stress-strain curve, which was observed in smaller specimens. Another reason for the reduction in peak strain could be the increased number of abnormalities in the specimen as the size increased.



a) 0% fibers



b) 1% fibers



c) 2% fibers

Figure 3. Stress vs Strain – Size effect (1 MPa = 145 psi)

Table 4. Peak stress of different specimens

Specimen Name	Peak stress (psi)
S1-22-0	522
S1-24-0	979
S1-44-0	1164
S1-22-1	1089
S1-24-1	1325
S1-44-1	1184
S1-22-2	1604
S1-24-2	1823
S1-44-2	1437

Note: (1 MPa = 145 psi)

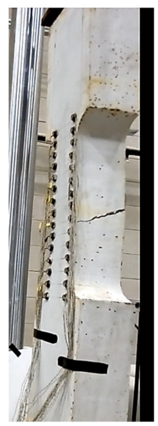


Figure 4. Out of plane bending observed during a 4 in. x 4 in. specimen test

4.2. Effect of Gauge Length

UHPC typically exhibits two different types of behaviors in tension, one with strain hardening and one without strain hardening. Figure 5 shows the typical stress vs strain curve of UHPC with strain hardening phase (Naaman, 2007). During strain hardening, several micro-cracks form along the length of the specimen and when one these micro-cracks transforms into a wider local crack, the resistance of the specimen goes down leading to a softening zone. As the behavior of the specimens was similar, the stress-strain curves for only one specimen (S1-22-1) are chosen for explanation. Figure 6a shows the stress-strain curves of S1-22-1 with different gauge lengths varying from 14 in. (355.6 to 1 in. (25.4 mm) and Figure 6b shows the stress-strain curves highlighting the strain hardening (micro-cracking) phase for 1 in. (25.4 mm) gauge lengths chosen at three different locations, one across the local crack, one below the local crack and one above the local crack. The strain hardening (micro-cracking) portion varied with the gauge length (Figure 6a) and also with the location of chosen gauge length (Figure 6b), which indicates the irregular distribution of the micro-cracks along the length. This resulted in different peak strain values (see Table 5), which play an important role in the design of elements. For example, if a typically used gauge length of 4 in. (101.6 mm) is chosen as reference, the peak stress of 1089 psi (7.51 MPa) occurs at a strain of 0.00223 in./in., but at the same strain level the stress is much lower for other gauge lengths viz., 921 psi (6.35 MPa) for 14 in. (355.6 mm), 1003 psi (6.91 MPa) for 8 in. (203.2 mm) , 903 psi (6.22 MPa) for 2 in. (50.8 mm) and 775 psi (5.34 MPa) for 1 in. (25.4 mm). The actual capacity of the structural element would be much lower than the design capacity calculated using the stress-strain curves generated using 4 in. (101.6 mm) gauge length.

The decrease in gauge length increased post peak softening zones and ultimate strain values, which can be related to the ductility of the specimen. Table 5 shows the values for peak strain, area under the stress-strain curves and the ultimate strain at 50% drop from the peak stress, for different gauge lengths varying from 14 in. (355.6 mm) to 1 in. (25.4 mm). The values for 4 in. x 4 in. (101.6 mm x 101.6 mm) are not listed due to the negative strain values caused by out of plane bending. It was observed that, the ratio of increase in these values with the decrease in the gauge length varies between the specimens. If the tensile capacity of the UHPC is planned to be used in the design, appropriate gauge length based on the expected crack spacing should be chosen, as this will have significant effect on the strength and deformation calculations. Further study is needed with larger samples sizes, and also to correlate the structural capacity of full scale UHPC elements from experiments and the analytical capacity from the stress-strain curves with different gauge lengths.

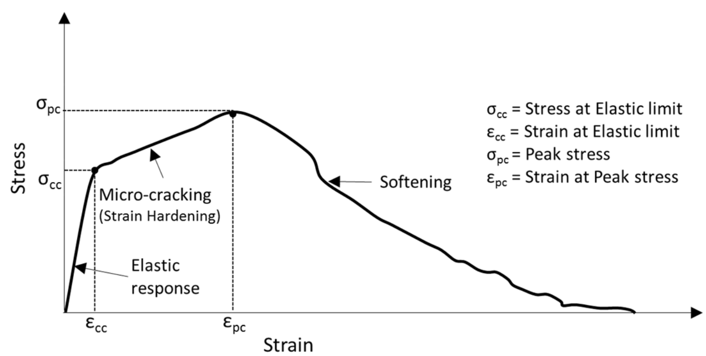
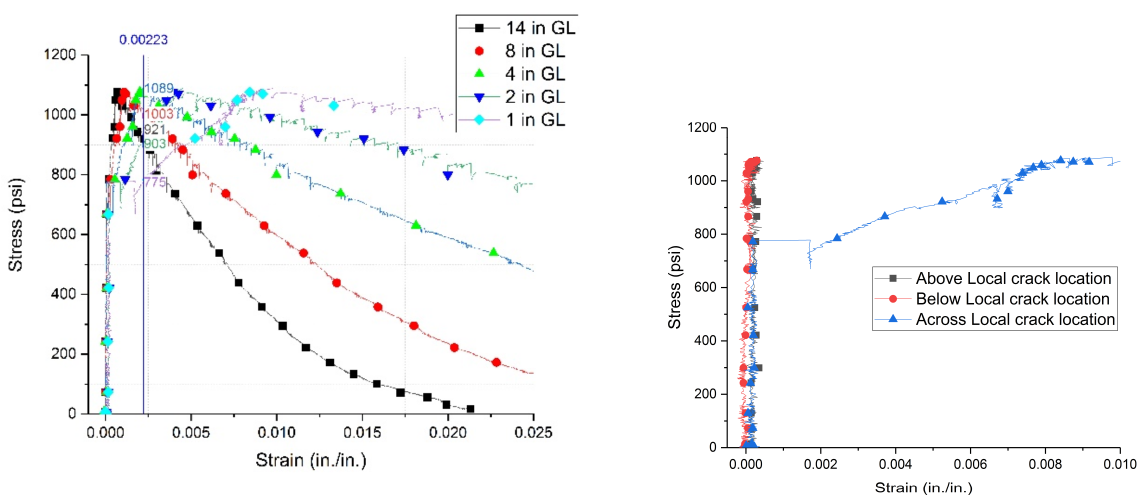


Figure 5. Generalized tensile response of UHPC exhibiting strain hardening (Naaman 182)



a) Different Gauge Lengths **b) Micro-cracking for different 1 in. Gauge lengths**

Figure 6. Stress vs Strain curves of S1-22-1 – Effect of Gauge length (Note: 1 MPa = 145 psi)

Table 5. Effect of Gauge length on various parameters

Gauge Length	S1-22-1			S1-22-2			S1-24-1			S1-24-2		
	Strain at Peak stress (ε_{pc})	Strain at 50% drop	Area under the curve	Strain at Peak stress (ε_{pc})	Strain at 50% drop	Area under the curve	Strain at Peak stress (ε_{pc})	Strain at 50% drop	Area under the curve	Strain at Peak stress (ε_{pc})	Strain at 50% drop	Area under the curve
14 in	0.00074	0.0065	8.07	0.00107	0.006	10.87	0.00019	0.006	9.46	0.0002	0.003	7.92
8 in	0.00123	0.011	14.05	0.0011	0.010	18.62	0.00025	0.010	16.48	0.00022	0.059	13.7
4 in	0.00223	0.022	27.59	0.00149	0.018	35.38	0.00047	0.021	33.1	0.00027	0.012	27.5
2 in	0.0045	0.044	47.63	0.00219	0.036	70.22	0.00078	0.043	65.37	0.0002	0.02	49.9
1 in	0.00978	0.096	76.48	0.00314	0.074	145.1	0.0013	0.084	108.17	0.00041	0.038	93.1

Note: 1 in. = 25.4 mm

5. Conclusions

This study evaluated the effects of size and gauge length on the tensile stress-strain response of UHPC. Nine dog bone shaped specimens made out of UHPC with different fiber ratios were tested in direct tension. The following conclusions can be drawn from this experimental study:

1) UHPC in tension does not tend to have any significant and consistent size effect in relation to the fiber volume.

2) The peak strain values are highly sensitive to the chosen gauge length. The micro-crack distribution is not uniform along the length of the specimens, which affects the peak strain of UHPC in tension.

3) The gauge length used to generate the design stress-strain curves should be based on the overall behavior of the element rather than selecting a smaller area and assuming similar behavior of the complete element.

3) The increase in the area under the stress-strain curves and ultimate strains also depends on the gauge length and the increase varies between the specimens of different sizes and fiber content.

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