Experimental Mechanics (2016) 56:1179–1190
DOI 10.1007/s11340-016-0154-1

Coupled Hydraulic System for Tensile Testing in Compression-only Machines

B. Reichard[1] · L.K. Stewart[1] · M. Weaver[2] · K.B. Morrill[2]

Received: 1 October 2015 / Accepted: 4 March 2016 / Published online: 1 April 2016

Abstract Fracture theory for normal strength concrete has thoroughly been studied over the past decades. Through indirect and direct tensile testing techniques, the post-peak softening response of conventional concrete has been established and utilized in analysis and design. However, for more recently developed concrete materials (e.g. fiber reinforced, high performance) under complex loading conditions, the required fracture properties to predict response are extremely limited. Considering this lack of knowledge, the objective of this research was to develop a uni-axial tensile testing technique to attain the post-peak softening response for ultra-high performance concrete for ultimate use in conjunction with an applied confining pressure system. Specifically, this research was conducted for implementation into an existing, large compression-only machine at the US Army Engineer Research and Development Center (ERDC). The new methodology enabled the existing testing frame to apply a stiffening force, while an external hydraulic plunger cylinder performed the tensile test. The scheme enables tensile testing under confining pressures in the compression-only machine.

Keywords Concrete · UHPC · Softening · Multi-axial testing · Compression machine · Tension testing

✉ L.K. Stewart
lauren.stewart@ce.gatech.edu

B. Reichard
breichard3@gmail.com

M. Weaver
weaver@kcse.com

K.B. Morrill
morrill@kcse.com

1 School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA, 30332, USA

2 Karagozian & Case, 700 N Brand Blvd Suite 700, Glendale, CA 91203, USA

Introduction

Concrete is one of the most widely used structural, building materials. It is relatively inexpensive with readily available constituent materials, provides great fire resistance and durability, and has large compressive strengths. However, its tensile capacity is very low, roughly one-tenth of that in compression. Because of this, concrete design, in the past, was based on an elastic, zero tensile capacity approach (Fig. 1(a)). In actuality, under uni-axial tension, concrete is a quasi-brittle material that exhibits a non-linear, post-peak softening response similar to that shown in Fig. 1(b). It has notable tensile toughness and energy dissipation ability, which is typically not taken into consideration for structural design. This response falls under the realm of fracture mechanics and is directly related to crack initiation and energy release during crack propagation. While the utilization of these properties may be insignificant in typical building design, it is valuable in improving the analysis of dynamic and repeated (i.e. fatigue) loadings, high-performance concretes, bar anchorage, punching shear, penetration simulations, and thus is essential in improving overall structural safety.

The softening response of concrete was first adequately quantified into specific parameters with the development of the fictitious crack model (FCM). The nonlinear softening curve as well as the FCM parameters can be used to update concrete finite element (FE) models, such as the smeared

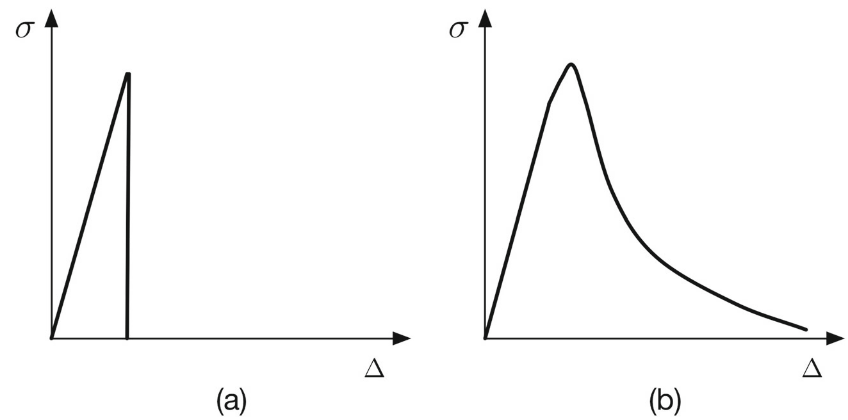


Fig. 1 Stress-displacement behavior under uni-axial tension for different idealized material types: (**a**) brittle and (**b**) quasi-brittle

crack model and concrete damage plasticity approach in FEM analysis programs (e.g. Abaqus, DIANA, LS-DYNA, etc.) [1–3]. These parameters have been implemented to create very complicated FE models to more accurately predict behavior of externally strengthened reinforced concrete members [4].

Through experiments that are performed with indirect test methods or direct tensile tests, the nonlinear tensile properties of varying types of concrete have been thoroughly researched and characterized. However, in the field of multi-axial behavior, the tensile softening response of concrete, especially ultra-high performance concrete (UHPC), is extremely limited. The US Army Corps of Engineers Engineer Research and Development Center (ERDC) is interested in the characterization of tensile post-peak softening properties for their UHPC under confinement. ERDC's testing machine of choice for such concrete material characterization efforts is a large four-post compressive loader that is compatible with a pressure vessel used to apply a confinement pressure to specimens. Unfortunately, this machine is not rated for tension, thus limiting its ability to perform extension tests where specimens do not fail in compression. Due to the presence of fibers in its constitutive cementitious matrix, it is not uncommon for UHPC to fail at relatively significant tension forces in extension. As such, the goal of this research was to develop a testing apparatus and associated methodology and protocol for the adaption of a large compression-only system into one that could apply tensile loading to obtain the post-peak response of UHPC in a controlled fashion.

Ultra-high performance concretes, in general, are distinguished by their high compressive strengths (over 200 MPa). Often, UHPCs, can be broadly characterized as a reactive powder concrete (RPC). RPCs are composed of fine aggregates and pozzolanic powders but do not include coarse aggregates like those found in conventional concrete. Alone, the concrete is marked by brittle behavior. To increase the toughness and post-crack load capacity of the brittle material, fibers consisting of steel, glass, cellulose and other materials are often added. The specimens considered in this paper consist of UHPCs with such integrated fibers.

This paper highlights the research procedure and apparatus developed for testing the UHPC, which includes the use of a hydraulic stiffening jack in series with the testing machine's actuator, the specific testing protocol as well as some initial results obtained during the proof of concept stage. Although this methodology is quite specific to the system used during the research program, the procedure and apparatus developed was found to be applicable for other experimental purposes. For example, the inclusion of the stiffening jack was discovered, as expected, to add a significant amount of stiffness to the testing system. This method (in the "passive" sense) could easily be used to modify existing testing machines with test frames that, at their current state, are too flexible (i.e. create deformations of the testing system that are too large) to capture the post-peak response. Additionally, the methodology and apparatus (in the "active" sense) is a relatively inexpensive means for modifying typical uni-axial compression-only systems for uni-axial tensile loading capability using only commercial, off-the-shelf components.

Review of Related Works

Uniaxial, or direct, tensile tests are generally agreed to be the most representative tests for determining the needed tensile parameters to characterize concrete in fracture mechanics. These parameters resulted from the development of the Fictitious Crack Model (FCM) by Hillerborg, Modeer, and Petersson in 1976. Prior to this time, fracture mechanic models were based on linear elastic and nonlinear plastic crack opening behavior, which poorly suit quasi-brittle materials such as concrete. The FCM was established on the basis of energy absorption per unit crack area. As the tip of a crack begins to reach its ultimate tensile strength, f_t, the crack starts to propagate and loses its cohesive stress capability. The larger the crack width, w, the lower the cohesive stress until it reaches a certain width, at which the crack can no longer support any stress [6]. The FCM splits the tensile failure of concrete into two separate processes as exhibited by the specimen representations in Fig. 2(a). One of these is the mostly linear, stress-strain relationship that occurs outside the fracture zone. The other process is the nonlinear, stress-crack displacement relationship that occurs in the fracture zone (Fig. 2(b)). The area under this tensile stress versus nonlinear crack opening response is used to determine the fracture energy parameter, G_F, in the FCM. Utilizing the modulus of elasticity in tension, E, along with the material parameters (G_F and f_t), the brittleness of the material can be quantified into a single property called the characteristic length, l_{ch}, as given in equation (1) [6].

$$l_{ch} = \frac{EG_F}{f_t^2} \quad (1)$$

Unlike indirect approaches, such as the splitting tensile, three-point bending, and compact tension tests, direct uni-axial tensile tests do not rely on inverse techniques, measure both f_t and G_f in a single experiment, and can also exhibit a uniform stress distribution over the fracture plane. While advantageous in some respects, the uni-axial tensile test can be difficult to perform correctly. With today's advanced technology some initial concerns that hindered direct tension tests (e.g. inadequate electronics, lack of development of closed-loop control servo-testing systems) are no longer major issues. However, even with improvements in controls and electronics, uni-axial tension tests are still complex with many aspects that need to be considered, including: effects of notches, size effects, boundary conditions and their relation to secondary flexure, gripping techniques, material structure, specimen alignment, environmental conditions, and the specific testing methods and techniques implemented (e.g. loading rate and control variable selection) [7–10].

One common necessity for uni-axial tensile tests is a stiff testing apparatus to allow for improved control and uniform crack opening. Some of the earliest direct tests were performed by Petersson. By heating large aluminum columns (roughly 12 cm in diameter), tensile deformation was induced between the two stiff concrete blocks leading to stable softening [11]. Cornelison et al utilized closed loop testing techniques, servo-controlled actuators, and a stiff guiding system in their experiments [12, 13]. To ensure uniform crack opening and increase testing stability, Carpinteri and Maradei implemented a three-actuator setup in their experiments to control to rotation [14].

While uni-axial tensile softening curves accurately describe concrete fracture properties under a uniform stress state, these stresses rarely act alone in three-dimensional structures. To gain a more realistic grasp of concrete fracture properties for implementation in FE models (e.g. reinforced concrete, penetration models), multi-axial stress states need to be examined. Bi-axial experiments are some of the earliest and most performed tests used to gain insight into multi-axial stress behaviors and failure contours of concrete. Figure 3 shows the typical strength and failure modes of concrete under combined stresses. Zone 2 is of special interest for the tensile softening properties of concrete. While not shown, every point in this region could be accompanied by a tensile softening curve. Predictably, the tensile strength of concrete decreases with increasing lateral confinement. Compared to uni-axial tests, bi-axial tensile tests show an increase in scatter [3, 15] and are more effected by concrete quality [3] and boundary conditions [16]. Few of these

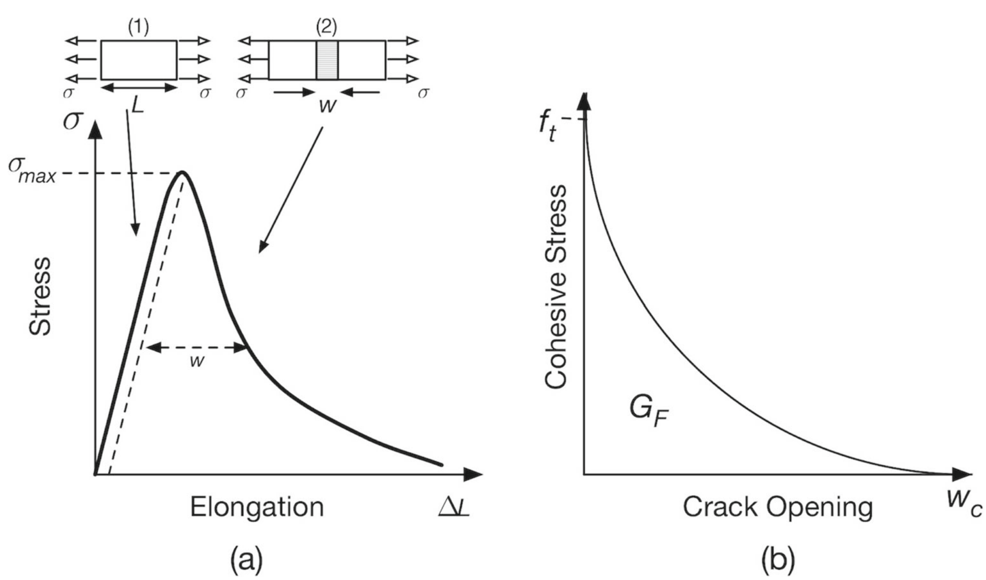


Fig. 2 Fictitious Crack Model processes and parameters: (**a**) total stress-displacement curve and (**b**) stress-crack opening displacement curve (from [5])

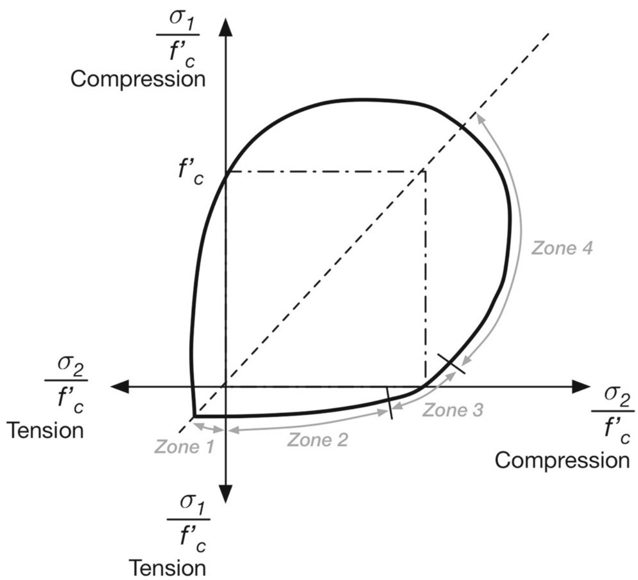


Fig. 3 Bi-axial failure contour (original results from [18])

tests have been documented, which is most likely due to the difficulty in performing and maintaining stability [3, 17].

Incorporating tri-axial and non-linear (i.e. softening) concrete characteristics into FE models result in more realistic material behavior predictions. However, tri-axial test data for concrete is limited, especially in the extension regime. "True/Full" multi-axial experiments require a specific testing machine made of three servo-valves for loading ability in up to three dimensions (depending on sample configuration) [3, 17]. These machines are uncommon, so typically hydraulic, tri-axial tests are performed on cylindrical samples to gain a better understanding of concrete multi-axial behavior. This method is limited because two stresses will always be equal. Hydraulic, compression tri-axial tests are common and much better characterized than tri-axial extension tests. While extremely beneficial in characterizing realistic concrete fracture properties, the latter are very rare. Some difficulties in performing uni-axial tensile tests under confining pressures deal with the fluid flow effects. Some tests use membranes to mitigate the influence of fluid pressure on the crack opening, also known as dry fracture. Others include this fluid pressure effect to get a more realistic idea of fracture mechanisms that take place in unsaturated and saturated materials. Incorporating the fluid effects, referred to as hydraulic fracturing, help estimate the fracturing process in oil wells, off-shore platforms, and dam structures [3]. Visser and Van Mier are some of the few researchers to have successfully performed stable uniaxial tensile tests under differing confining pressures [18, 19].

Although both uni-axial and multi-axial tensile testing techniques have proven to be successful, their complexities make it difficult to recreate and utilize in a typical structural laboratory for education and research purposes. The difficulty with multi-axial extension tests, specifically, has resulted in a very narrow characterization of concrete fracture under three-dimensional stress states.

Experimental Design & Technique

The experimental research presented in this paper encompasses work performed through two phases of investigations. Phase I was mainly concerned with the appropriateness/feasibility of incorporating an external hydraulic cylinder to improve testing stability, while Phase II went further in depth to improve on the overall testing system and methodology for ultimate use in multi-axial experiments.

Methodology

Prior to developing the uni-axial testing protocol, a bonding procedure for gripping of the concrete specimens was developed and varying instrumentation methods were investigated for use as possible feedback signals during closed loop testing. Once these aspects were determined, the feasibility and usefulness of implementing a stiffening jack in a typical load frame was studied. Initial tests utilized the hydraulic jack in a "passive" manner, meaning the jack impeded the load frame actuator during extension, but was not directly controlled. This passive technique could be directly applied into a typical load frame for additional stiffness. Later tests used the jack in an "active" approach whereby the load frame actuator was in a constant state of compressive stress while the jack, controlled by the feedback signal, performed the extension. The "active" technique could be implemented into a compression only load frame to execute a direct tensile test and then further utilized with a pressure vessel for tri-axial, hydraulic testing.

Test Setup

Specimen

Tests were performed on normal strength concrete (NSC), ultra-high performance concrete (UHPC), and surrogate PVC and acrylic specimens. Un-notched NSC and UHPC specimens were used to evaluate the effectiveness of the stiffener for tensile testing specific to concrete. Surrogate PVC and acrylic samples were used for troubleshooting of the test setup, ensuring functionality of the design. Important properties of these samples are listed in Table 1. Figure 4 presents the dimensions of the different samples used.

Due to its high strength and durability, 3M DP 460 epoxy was chosen as the attachment method for the concrete specimens. Specimens were glued onto flat steel end caps, which were chosen in lieu of grooved end caps due to negligible

Table 1 Specimen properties

Material	Notch	Critical diameter (mm)	Nominal height (mm)	Elastic modulus[a] (GPa)	Ultimate tensile stress[a] (MPa)	Attachment
NSC	No	50.8	114.3	30.0	3.9	3M epoxy
UHPC	No	50.8	114.3	83.0	6.8	3M epoxy
Acrylic	Yes	19.1	127.0	3.0	31.0	Threaded
PVC	Yes	19.1	127.0	2.8	62.1	Threaded

[a]Approximate

differences in results and also ease of attachment. To minimize effects of imperfections in the concrete samples near the boundaries and alignment issues during gluing, fillet glue lines were applied around the perimeter (Fig. 5) and an alignment jig was utilized to keep the specimen centered in the endcap.

Instrumentation

A simplified instrumentation plan was selected for the proof of concept study in order to test and refine the methodology. For this specific application, two DC LVDTs (250 DC-EC by Measurement Specialties) were used to measure axial displacement. This instrumentation is often the favored method in previous research [13, 14, 20]. For simplicity, in this proof of concept study, full specimen gage lengths (i.e. 11.5 cm (4.5 in)) were chosen to capture the crack location of the unnotched specimens as shown in Fig. 5. The average of the two LVDT readings was used as the feedback signal for closed-loop control. It has been shown that the control gage length greatly affects the stability of a test. If too large, the crack-opening rate becomes uncontrollable, and the specimen can rupture immediately. Even if a stable test is able to be performed, a large gage length may not report accurate local fracture zone behavior [13]. Because the main objective of this research is to analyze the effectiveness/possibility of implementing a stiffening jack, controlling displacement off the average of the full specimen-length LVDTs was deemed acceptable. However, recorded strains and crack openings should not necessarily be taken as the true material properties of the concrete specimens. A solution to allow for more accurate and reliable results is presented in "Discussion".

Testing System and Components

The experiments were conducted using a SATEC 100 kip testing frame in the Hi-bay laboratory at the Manufacturing Research Center (MARC) at Georgia Tech as shown in Fig. 5. A custom fabricated crosshead consisting of two MC13x50 channels was secured to the load frame columns in order to incorporate the stiffener (i.e. hollow plunger cylinder) into the test setup. The crosshead also improved the lateral stiffness of the testing system. Six 1.9 cm (0.75 inch) diameter, Grade 8 bolts per column were tensioned to 125 kN (28,000 lbf) each to ensure a rigid attachment. To protect the load frame columns and allow for a more

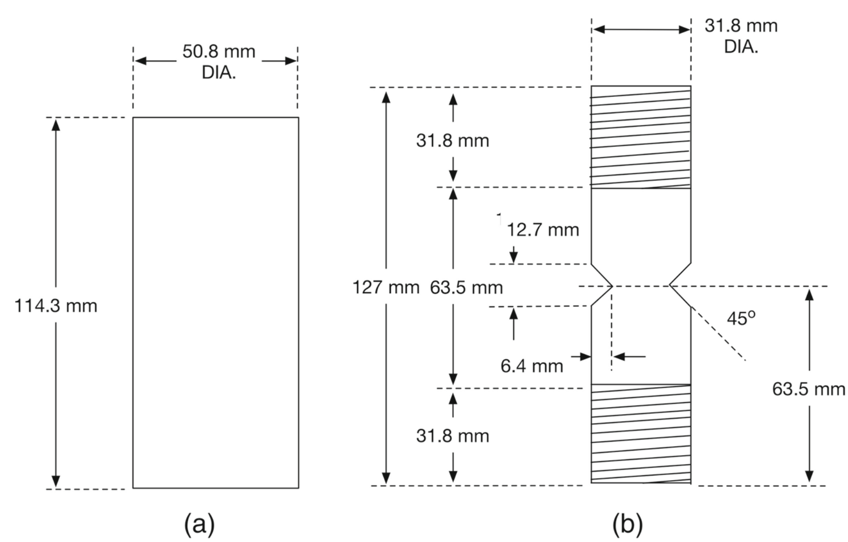
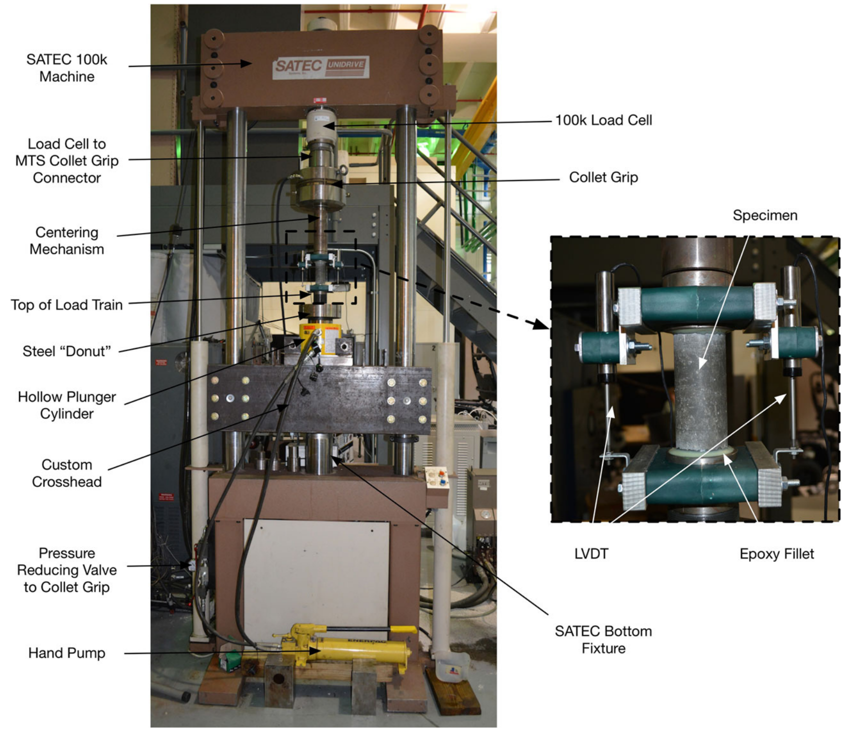


Fig. 4 Dimensions of samples: (**a**) NSC and UHPC, and (**b**) Acrylic and PVC

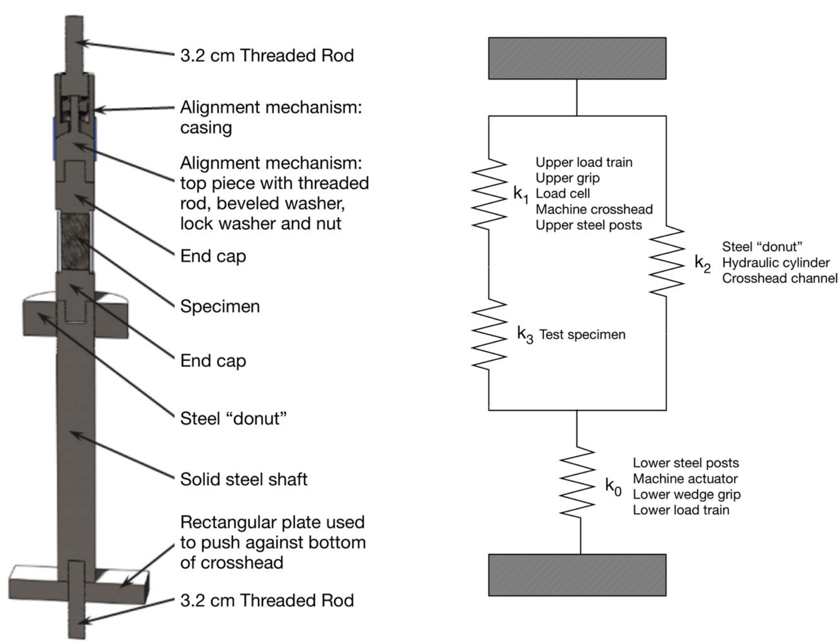
Fig. 5 "Passive" experiment setup



uniform distribution of clamping force, two aluminum billets, one on each side, were placed in firm contact with each of the columns.

An off-the-shelf 100-ton capacity hollow plunger cylinder (HPC) (Enerpac Model No. RRH-1001) was selected as the stiffener. The ability of this HPC to separate the force system within the load frame was made possible through the design of a custom fabricated load train as shown in Fig. 6(a). This specific component was used to implement the passive and active concepts. Figure 6(b) combines the testing system and components into a spring stiffness diagram, symbolizing the different load paths created by the incorporation of the HPC. A manual hand pump was used to pump hydraulic fluid into the cylinder and to maintain cylinder pressure for passive testing. The setup also included a 100 kip load cell, MTS collet grip, twin Moog valves, and a Hunger Hydraulic Actuator. The controller used during the test was the TestStar IIs Version 3.2C 929.

Fig. 6 Testing system (**a**) load train and (**b**) spring stiffness diagram



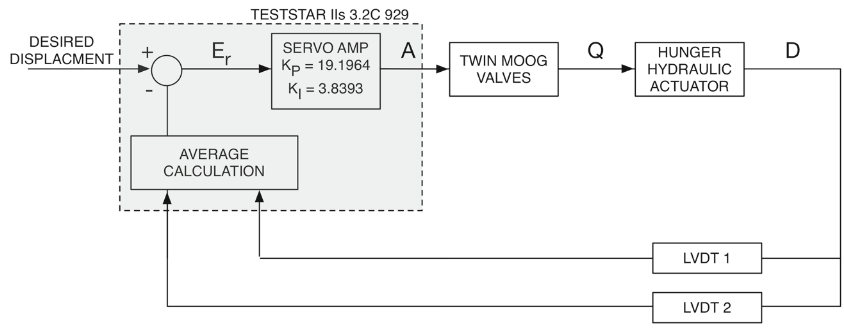


Fig. 7 Control block diagram for "passive" testing

The overall testing frame setup for passive tests is shown in Fig. 5. Passive testing utilized the feedback from the average of the LVDT readings to control the machine actuator while the HPC pressure was left uncontrolled. A block diagram for the passive test control scheme is shown in Fig. 7, where E_r is the error, K_P is the proportional gain, K_I is the integral gain, A is the amperage, Q is the hydraulic flow, and D is the displacement.

Active testing differed from passive by the inclusion of a load cell at the bottom of the load train and utilization of the Parker DFplus servo proportional valve to control the displacement of the HPC jack during testing. Both of these are shown in Fig. 8(a). The significance of the bottom load cell is to use its readings as feedback for the machine actuator control so that constant compression can be applied, emulating a compression-only load frame. During testing one command was sent to the machine actuator to hold the load in the bottom load cell at a constant force, while at the same time, another command was sent to the HPC jack to control the displacement of the average of the LVDTs. The latter command utilized the error in the average LVDT readings to send a +/- 10V signal to the Parker DFplus servo valve. This was undertaken through readout channels in the TestStar IIs controller. There was no transfer of data between these two loops. However, each loop was able to adjust to the physical variations driven by the opposing loop through use of its relative feedback signal to maintain the desired command. The variables in Fig. 8(b) are identical to those in Fig. 7 with the addition of V for the voltage.

Data Acquisition

Data were acquired through the TestStar IIs controller at varying intervals. Earlier tests initially used lower data acquisition rates (e.g. 1 point/sec and 2 point/sec), however it was deemed necessary to increase this rate to 20 point/sec in order to capture the full response of the concrete. The time, force measured in each load cell, both LVDT readings, and machine actuator position were monitored for each test performed. In analyzing the rotation that occurred during testing, the single LVDT readings were projected onto the sample. Pictures were taken after every test to document crack location and path. Crack propagation was documented during a few of the tests.

The results from the different phases were compared to give some validation to the repeatability of this uni-axial tensile testing scheme. Since the specific material properties of the concrete specimens were not known and from various batches, findings were not able to be validated by previous uni-axial tensile test data.

The resulting stress-crack opening curves for UHPC are approximated by an approach presented in multiple references [21, 22]. This method estimates the crack-opening width by subtracting residual deformation at peak stress

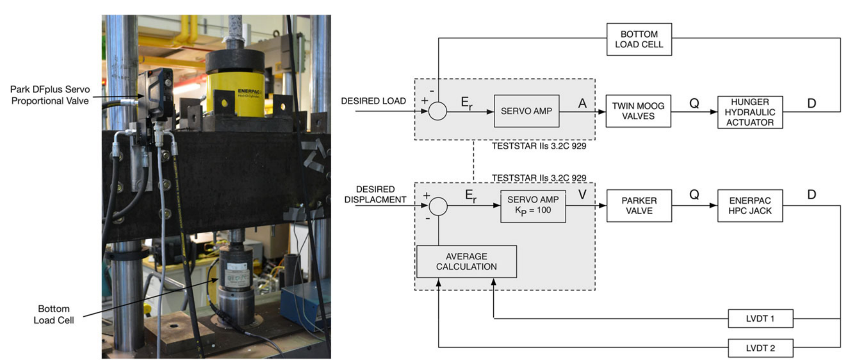


Fig. 8 Active testing (**a**) components and (**b**) block diagram

and the elastic deformation at any point on the stress-displacement curve outside the fracture zone from the specific deformation reading. The described method is used to better interpret the results. However, as previously stated, the large gage lengths influence the findings; therefore, recorded strains and crack openings should not be taken as the UHPCs true material properties.

Test Procedure

Different variables were altered during active and passive testing to help determine the critical aspects of devising a unique uni-axial tensile testing procedure. These independent variables included test type (passive and active tests), specimen type (UHPC and NSC), load rate, length of epoxy cure time, boundary conditions (centering mechanism which allows for rotation and fixed adapter), bottom load train stiffening force, and compressive pre-load in the specimen. The effects of a few of these variables on load-displacement curves are compared in "Results". All experiments performed strictly followed either a passive or active testing procedure. The specific steps in these procedures are listed as follows:

Passive Testing Procedure

1. Set sample along with instrumentation in load frame and pressurize the collet grip.
2. Apply 3.5 MPa (500 psi) to the steel donut through the manual hand pump.
3. Pre-load the sample to a specified compression force.
4. Begin loading the sample in tension to a specified tensile force (e.g. 70 % of tensile load capacity) over a period of 10 seconds.
5. Continue tensile loading through a constant displacement rate of either the machine actuator or the average of the two LVDTs.

Active Testing Procedure

1. Bolt load train donut to HPC.
2. Manually command force in bottom load cell to zero force with the controller.
3. Set sample along with instrumentation in load frame.
4. Move the top crosshead and HPC jack so that the specimen is securely located inside the collet grip and pressurize the grip.
5. Manually command the bottom load cell to a specified compression force.
6. Using the error of the LVDT feedback, manually command the HPC cylinder until the top load cell is at a desired pre-load compressive force.
7. Perform the uni-axial tensile test where the specified bottom load cell force is held constant, while the HPC jack is displaced at a constant rate utilizing the feedback from the LVDT readings.

Results

Initial tests were performed on surrogate acrylic samples to test the effects of the HPC stiffener for uni-axial tensile testing. Figure 9 shows a representative load-displacement plot for these tests. To note, all displacement values are the average of both LVDT readings. Unless otherwise stated, this holds true for all plots in this section. With the incorporation of the stiffening jack, the axial stiffness of the global testing system increased by a factor of fifteen by limiting the

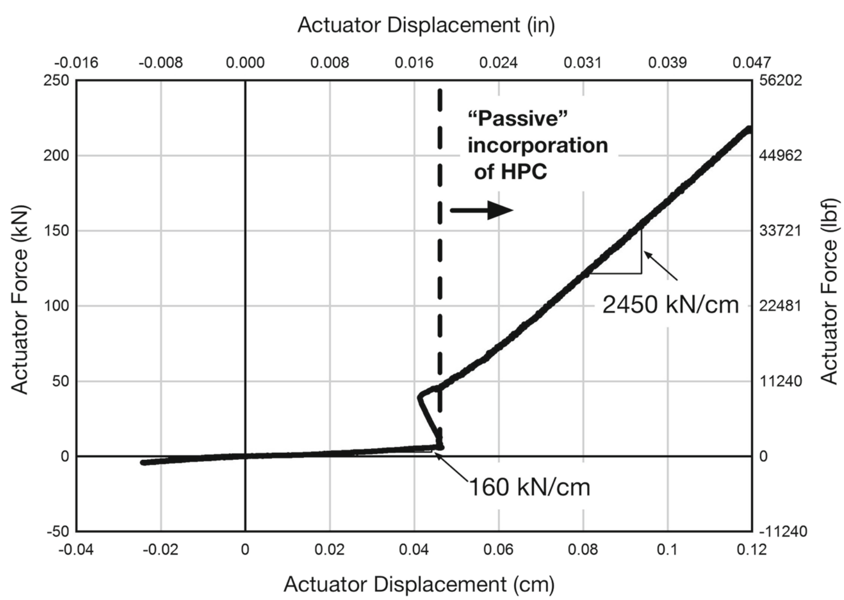


Fig. 9 Representative load-displacement curve for an acrylic sample that displays effect of stiffening jack on test system

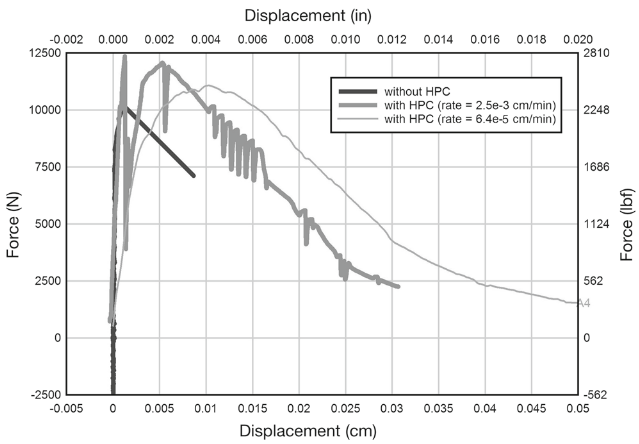


Fig. 10 "Passive" test results for UHPC with and without HPC at various rates

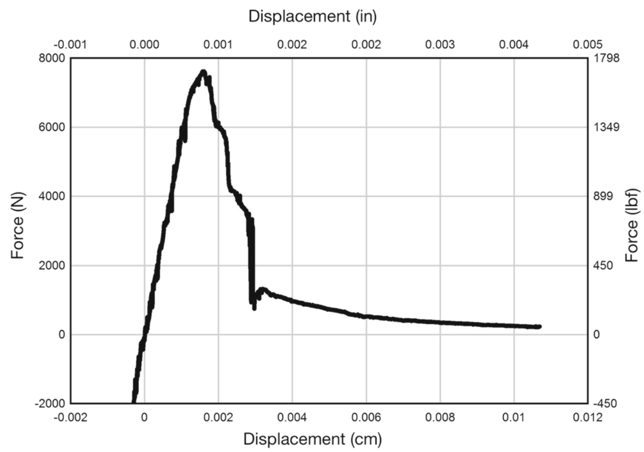


Fig. 11 "Passive" test results for NSC with HPC

importance of spring k_0 (Fig. 6). This large increase greatly improves the stability of tensile testing of brittle and quasi-brittle materials as evident in the UHPC test results shown in Fig. 10. Without it, stable uni-axial tensile tests were unable to be performed on UHPC with the SATEC system. It should be noted that the k_1 and k_3 springs in Fig. 6 remain unaltered, and this branch could still serve to promote specimen failure if too compliant. Additionally, the load rate also was critical in ensuring the full characterization of the softening curve. Figure 10 also gives the output from two tests with the HPC at two loading rates. From the plot, the faster load rate drops the load at multiple locations, but is able to recover.

Additionally, it was observed that as the material becomes more brittle (PVC = least brittle, NSC = most brittle), the ability to maintain stability and obtain the total post peak response becomes more difficult. For the PVC and UHPC specimens, the entire softening response was captured without a drop in load. For the NSC test, the system was able to capture the first half of the softening response and then dropped the load as shown in Fig. 11. Due to the brittleness of NSC and large measured gage length, no full softening curves were captured for those specimens using the "passive" method.

Once the testing protocol was finalized, eight additional uni-axial tensile tests were performed on UHPC using the "passive" and "active" testing procedures given in "Test Procedure". A test matrix including the relative test number, displacement rate at peak load (i.e. critical load rate), machine stiffening force, and stability of each test is presented in Table 2. The successful tests (meaning those without premature failure or stability issues) for UHPC are shown in Fig. 12. Influences in the stability and in some cases premature failure, seemed to be associated with rotational stiffness (i.e. boundary conditions), feedback signal, and specimen pre-load [9].

The UHPC tests were overall positive with a 50 % success rate of maintaining stability over the duration of the test. This success rate is often acceptable for uni-axial tensile tests on unnotched specimens. The load-displacement curves of these successful tests show high precision. These results are promising and help validate the "active" stiffener scheme which was one of the main goals of this research. The higher ductility, especially due to fiber crack-face bridging, is the most likely reason UHPC tests were stable under both the "passive" and "active" loading conditions.

The amount of stiffening force applied by the load frame actuator during active testing was altered to analyze its specific effects on the stability of the testing scheme. The results show that the tests with larger, lower stiffening forces (e.g. A1 and A4) tended to have increased stability during softening. While test A5 suddenly lost stability, it partially recovered and was stable throughout the remainder of the test. A2 and A3, which had stiffening forces of 2,200 N, lost stability and did not recover. It seems from these results that an increase in lower stiffening force increases testing stability, but certain tests in this comparison could have been influenced more by other factors, which may also have contributed to testing instability, diminishing the effect of the stiffening force [9]. Future research is needed to firmly establish this conclusion.

Discussion

For comparison and relation to the FCM, the stress-crack opening and normalized stress-crack opening curves were approximated for UHPC tests P1, P2, A1, and A4. The resulting mechanical tensile properties from these tests have been compiled in Table 3. The results give similar softening relations for all specimens. When the stress is normalized,

Table 2 UHPC test matrix

Test Type	Test No.	Critical Load Rate (mm/min)	Stiffening Force (N Compression)	Post-peak
Passive	P1	1.3e-3	N/A	Yes
Passive	P2	6.4e-4	N/A	Yes
Active	A1	6.4e-4	3,300	Yes
Active	A2	7.6e-4	2,200	No[a]
Active	A3	7.6e-4	2,200	No[b]
Active	A4	6.4e-4	4,450	Yes
Active	A5	6.4e-4	3,300	No[a]
Active	A6	6.4e-4	44,500	No[c]

[a]Lost stability at peak load, but partially recovered
[b]Premature failure / loss of stability
[c]Failure due to peeling epoxy at end cap interface

the differences become even less obvious. One significant discrepancy between tests is the relatively low elastic modulus of test P2. This difference led to the more brittle characteristic length of P2 in spite of its high fracture energy.

From the results in Table 3, the characteristic length of the UHPC tested can be taken as 800 mm. This result makes sense when compared to typical characteristic lengths of more brittle materials: glass = 10-6 mm [23], hardened cement paste = 5-15 mm [6, 23] mortar = 100-200 mm [6, 23], high strength concrete (42-103 MPa) = 300-500 mm [21], normal concrete = 200-500 mm [6, 23]. However, when compared to previous softening curves with glass fibers, the fracture energy seems low. Barros et al. tested typical glass fiber reinforced concrete (GFRC) specimens and determined an ultimate tensile strength and fracture energy of 4.4 MPa and 1912 N/m, respectively [24]. One possible explanation for these differences is the large measured gage length (i.e. 11.4 cm) utilized in this research.

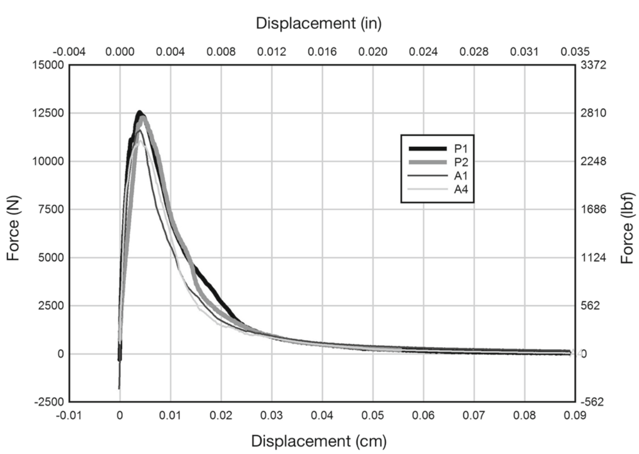


Fig. 12 Successful "passive" and "active" force-displacement results for UHPC

Other research has shown that with a larger gage length, the elastic modulus decreases and the slope of the descending branch of the softening curve increases, resulting in less apparent ductile behavior [13]. This measured gage length effect has also been shown to occur in GFRC specimens [25]. Another possible explanation for discrepancies is the fiber alignment, type, and distribution [3, 20, 26]. Barros et al. showed that the distribution of fibers due to specific mixing techniques can also greatly affect the mechanical properties [24]. While the specific mixing methods and proportions of fibers are unknown for the samples tested, from analyzing the fracture planes of the UHPC specimens it was determined that the fiber quantity and distribution for the UHPC samples were highly variable. Post test examinations of the specimen for Test A5, in particular, had a low percentage of fibers, which may attribute to the less than expected fracture energy for a fiber reinforced concrete (FRC).

While the overall testing scheme devised was successful, the obtained data on UHPC may be misrepresenting due to the large measured and control gage lengths. The full-specimen gage length utilized is not small enough to confidently determine fracture material properties. For accurate and reliable stress-crack opening relations of normal concrete, it has been shown that a minimum gage length of half of the specimen length is required [13]. However more accurate results will benefit from smaller lengths assuming the fracture zone is captured. Because of this, it is the opinion of the researchers that gages closer to a quarter of the specimen length should be chosen for measurements. Therefore for the concrete specimens tested in this research (length of 11.4 cm) a gage length of 3.2 cm is much more appropriate. Since un-notched specimens are to be tested, a series of six gages will be required around the specimen to insure crack capture. Assuming accurate data will result from fracture zones occurring in the middle half of the specimen, gages will only encompass this area. Stable UHPC uni-axial

Table 3 Approximate mechanical properties of UHPC specimens

Test No.	Elastic modulus, E (GPa)	Tensile strength, f_t (MPa)	Fracture energy parameter, G_F (N/m)	Characteristic length, l_{ch} (cm)
P1	48.9	6.2	705.3	89.8
P2	31.8	6.2	678.2	56.2
A1	40.8	5.8	581.7	71.3
A4	45.0	5.5	559.8	82.5

tensile tests were performed using the feedback from the full-specimen gage length. However maintaining stability under confining pressures will most likely be more difficult. Therefore, it is proposed for future research that two gages, three inches in length, are to be used as feedback to control the test. If testing is still unstable, the maximum opening rate of the smaller gages may be required.

Conclusions

The main objective of this research was to develop a novel, uni-axial testing scheme, so that the fracture properties of concrete could be more broadly and easily studied. The uni-axial tensile testing results from this research validate the following: (1) the capability of an off-the shelf HPC (Enerpac Model No. RRH-1001) to improve the stiffness of a typical MTS or SATEC load frame to allow for stable, uni-axial tensile testing of UHPC specimens, and (2) the ability to perform a uni-axial tensile test by actively controlling a HPC using specimen feedback while maintaining a constant compressive force in the machine actuator. The latter of which is vital in implementing this testing scheme into compression-only load frames for potential multi-axial studies inside a pressure vessel.

Acknowledgments This research was sponsored by a Small Business Innovative Research (SBIR) grant from the United States Army Engineer Research and Development Center. Any opinions, findings, conclusions or recommendations are those of the authors and do not necessarily reflect the views of other organizations.

References

1. Aure T, Ioannides A (2010) Simulation of crack propagation in concrete beams with cohesive elements in abaqus. J Transp Res Board 2(2154):12–21
2. Chaudhari S, Chakrabarti M (2012) Modeling of concrete for non-linear analysis using finite element code abaqus. Int J Comput Appl 44(7):14–18
3. van Mier J (1996) Fracture processes of concrete: assessment of material parameters for fracture models. CRC Press
4. Farah K, Sato Y (2011) Uniaxial tension behavior of reinforced concrete members strengthened with carbon fiber sheets. J Compos Constr:215–228
5. Kumar S, Barai SV (2011) Concrete fracture models and applications. Springer
6. Hillerborg A, Modeer M, Petersson P (1976) Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cem Concr Res 6 (6):773–782
7. Akita H, Koide H, Tomon M, Han S (2002) Three misunderstandings in uniaxial tension test of concrete. In: Proceedings of the 5th ACI International Conference. Innovations in Design with Emphasis on Seismic, Wind, and Enviornmental Loading; Quality Control and Innovations in Materials/Hot-Weather Concreting, pp 405–414
8. van Mier J, van Vliet M (2002) Uniaxial tension test for the determination of fracture parameters of concrete: state of the art. Eng Fract Mech 69(235–247)
9. Reichard B (2015) Uniaxial tensile testing technique to obtain softening response of ultra-high performance concrete under confining pressures. PhD thesis, Georgia Institute of Technology
10. Zhou F (1995) Influences of notch size, eccentricity and rotational stiffness on fracture properties determined in tensile tests. Fracture Mechanics of Concrete Structures
11. Petersson P (1981) Crack growth and development of fracture zones in plain concrete and similar materials. PhD thesis, Lund University
12. Cornelissen H, Hordijk D, Reinhardt H (1986) Experimental determination of crack softening characteristics of normalweight concrete. Heron 2:45–56
13. Hordijk D (1991) Local approach to fatigue of concrete. PhD thesis, Delft University of Technology
14. Carpinteri A, Maradei F (1994) Three-jack solution to obtain a truly stable and symmetric tensile concrete test. Exp Mech:19–23
15. Kupfer H, Hilsdorf H, Rusch H (1969) Behavior of concrete under biaxial stresses. ACI J Proc 66:656–666
16. Gerstle K, Linse D, Bertacchi P, Kotosovos M, Ko HY, Newman J, Rossi P, Schickert G, Taylor M, Traina L, Zimmerman R, Bellotti R (1978) Strength of concrete under multiaxial stress states. In: Douglas McHenry Int'l Symposium on 'Concrete and Concrete Stru, American Concrete Institute, American Concrete Institute, pp 103–132
17. van Mier J (1984) Strain-softening of concrete under multiaxial loading conditions. PhD thesis, Eindhoven University of Technology
18. Visser J, van Mier J (1995) Tensile hydraulic fracture of concrete and rock. In: Wittmann F (ed) Fracture mechanics of concrete structures. FRAMCOS-2, AEDIFICATIO Publishers
19. Visser J, van Mier J (1998) The mechanical behaviour of hydraulic fractured, possibly saturated materials. In: Publishers A (ed) FRAMCOS-3, fracture mechanics of concrete structures, pp 269–280

20. Li Z, Kulkarni S, Shah S (1993) New test method for obtaining softening response of unnotched conrete specimen under uniaxial tension. Exp Mech
21. Li Q, Ansari F (2000) High-strength concrete in uniaxial tension. ACI Mater J:49–55
22. Zhao Z, Zhang J, Zhou H, Shah S, Zhao Z (2011) Two methods for determining softening relationships of dam concrete and wet-screened concrete. Adv Struct Eng:1125–1138
23. Karihaloo B (1995) Fracture mechanics and structural concrete. Longman Publishing Group
24. Barros J, JA Figueiras CV (1994) Tensile behaviour of glass fibre reinforced concrete. In: Comunicações a Conferências Internacionais. ISISE
25. Gettu R, Mobasher B, Carmona S, Jansen D (1996) Testing of concrete under closed-loop control. Advanced Cement Based Material 3(2):54–71
26. Wang Y, Li V, Backer S (1990) Experimental determination of tensile behavior of fiber reinforced concrete. ACI Mater J 87(5):461–468