Comparison of Steel Fibers and Transverse Steel Reinforcement for Shear Capacity in Reinforced Ultra High Performance Concrete Beams

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Abstract

Ultra high performance concrete (UHPC) is a class of cementitious composites comprised of a mortar mix containing a relatively large percentage of cement and short, randomly disbursed fibers. Its high strength and ability to maintain narrow crack widths lend the material to a wide range of applications. When reinforced with deformed steel bars, proper care in design is required to make efficient use of both the longitudinal steel in tension and UHPC fracture toughness in compression. Recent studies have shown that a high reinforcement ratio combined with a low fiber volume fraction leads to increased ductility and a favorable, gradual failure path. The objective of this research is to study the response of steel reinforced UHPC beams (R/UHPC) with a high shear demand from both a high reinforcement ratio (above 4%) and low shear span-to-depth ratio (near two). Four small scale R/UHPC beams were experimentally tested. Transverse steel reinforcement ratio and steel fiber volume fraction were varied. Experimental results show that more narrow stirrup spacing with a lower fiber volume allowed the R/UHPC beams to more fully utilize the longitudinal steel properties in tension and UHPC properties in compression. Additionally, results indicate that R/UHPC beams with more transverse steel and fewer steel fibers facilitated a higher peak load, more multiple cracking, and smaller shear crack widths than those with less transverse steel and more steel fibers.

Keywords: Fiber volume fraction, reinforced ultra high performance concrete beams, shear, transverse steel.

1. Introduction

Ultra high performance concrete is a cementitious material that possesses high compressive strength in excess of 150 MPa (22 ksi) (Pourbaba et al., 2019). It also includes steel fibers, typically between 1-3% by volume, in order to provide tensile strength, pseudo-strain hardening behavior and crack width control (Bermudez et al., 2022). The fibers also provide compressive fracture toughness to prevent spalling (Kodur et al., 2018) and aid in confinement and bond when reinforced with steel bars (Hung and Chueh, 2016). The applications of UHPC are numerous; the material can be used for connections between bridge components, pre-stressed girders, as well as highway overlays. R/UHPC, along with other longitudinally reinforced high-performance fiber-reinforced cementitious composite beams, have demonstrated two dominant failure paths in flexure: after crack localization in the UHPC or after gradual strain hardening of the steel reinforcing bars. Failure path has been shown to be a function of both the steel hardening force capacity and the tensile capacity of the UHPC (Shao and Billington, 2019a). Failure after gradual strain hardening is more preferable to failure after crack localization due to R/UHPC beam's increased ductility and warning before failure when strain hardening occurs.

In order to take better advantage of the composite material properties of R/UHPC, allow for a ductile failure path and maintain warning before failure under extreme loading conditions, increasing the steel reinforcement ratio beyond what would normally be acceptable for ordinary reinforced concrete is recommended (Shao and Billington, 2019b). The higher reinforcement ratio drives a lower neutral axis in the cross-section and encourages higher compressive strain in the UHPC. R/UHPC beams with a relatively low steel fiber volume fraction, e.g., 0.5% or 1%, have been proposed to compensate for the additional cost of longitudinal steel while still maintaining enough compressive fracture toughness to prevent spalling (Shao and Billington, 2022).

The combination of a large longitudinal steel reinforcement ratio, that increases both shear demand and capacity of the beam, with a low steel fiber volume fraction, that reduces shear capacity, could produce undesirable, abrupt shear failures. Jin et al. (2015) concluded that R/UHPC shear capacity is affected primarily by shear span, then steel fiber volume fraction, longitudinal steel, and finally transverse steel. The purpose of this study is to explore shear response and capacity of R/UHPC beams in specimens that experience a high shear demand caused by a large reinforcement ratio and a low shear span.

In one study of R/UHPC beams with a shear span-to-depth ratio of 2.8, the presence of steel fibers without transverse reinforcement prevented shear failure when the longitudinal reinforcement ratio was 0.8% and 1.2% (Yavas and Goker, 2020). At reinforcement ratios of 1.7% and 2.2%, however, without transverse steel, the R/UHPC beams exhibited shear failure. Simply adding more steel fibers does not increase the ductility of the beam, however. R/UHPC beams with a 1.83% reinforcement ratio and a shear span-to-depth ratio of 2.125 were tested with no transverse steel. Increasing fiber content from 1% to 2% resulted in more localized reinforcement yielding and thus, reduced beam ductility (Gomaa and Alnaggar, 2019). Results indicated tailoring of both the fiber content and reinforcement ratio is required to ensure strain-hardening behavior and specimen ductility in R/UHPC beams.

In another study of R/UHPC beams with 1.5% steel fibers by volume and no transverse steel, specimens exhibited similar ductility to other high strength concrete specimens reported in the literature (Kodur et al., 2018). With reinforcement ratios of only 0.90% and 1.2%, however, the beams were not heavily reinforced. In R/UHPC beams with a 7.6% reinforcement ratio, shear span-to-depth ratios of 1.5 or 3.3, and fiber volume fractions ranging from 0.75% to 2.25%, fibers alone provided sufficient shear strength per ACI 318-14 (Bermudez and Hung, 2019). The study used very high longitudinal reinforcement ratios and short shear spans, creating a high shear demand, but hooked steel fibers of different lengths were used and determined to be key in enhancing shear properties of the R/UHPC beams. From the literature, it is clear that efficient use of the entire R/UHPC beam's cross section requires a high longitudinal steel reinforcement ratio. But more investigation is required to account for shear strength contributions from straight steel fibers and transverse steel when shear demand is high.

2. Methods

In this study, four small-scale R/UHPC beams were cast and experimentally tested after 28 days. Longitudinal and transverse reinforcement ratios were varied, as was the steel fiber volume fraction. Shear span was kept constant. A proprietary UHPC pre-mix called DUCTAL, produced by LafargeHolcim, was used for this study. Steel fibers were 0.0079 inches (0.2 mm) in diameter and 0.51 inches (13 mm) long. Mixing was done in a horizontal pan mixer according to manufacturer's mix proportions (Table 1) and specifications. The standard DUCTAL mix uses 2% steel fibers by volume, V_f, but in this study, specimens with both 0.5% and 1.0% steel fibers by volume were cast by placing UHPC into one end of the form.

Table 1: UHPC Mix Proportions

Constituent	lb per yd^3 (kg per m^3)
DUCTAL Dry Premix	3700 (2195)
Water	193.8 (115)
Superplasticizer	50.6 (30)
Steel Fibers	131.5 or 65.7 (78 or 39)*

*131.5 lb (78 kg) for $V_f = 1\%$, 65.7 lb (39 kg) for $V_f = 0.5\%$

At 28 days, the average compressive strength was 18.5 ksi (128 MPa) and 14.1 ksi (97.2 MPa) for the 0.5% and 1% volume fractions, respectively, as measured by 3-inch (75 mm) diameter cylinders (ASTM C1856). Authors noted that the 1% steel fiber volume fraction mix resulted in cylinders and test specimens with poorer consolidation, likely related to an increase in time taken to make minor batching adjustments during the mixing process for optimal flowability per manufacturer guidelines while the material underwent the hydration process. The modulus of rupture was 1.92 ksi (13.2 MPa) and 1.93 ksi (13.3 MPa) for the 0.5% and 1% mixes, respectively as measured by third point bending tests of 4 in. × 4 in. (101 mm × 101 mm) rectangular prisms. Grade 60 No. 6 (20M) bars were used for longitudinal reinforcement, and Grade 100 No. 3 (10M) bars were used for transverse reinforcement. Yield and ultimate strength of the transverse reinforcement was 127 ksi (876 MPa) and 169 ksi (1166 MPa), respectively. Yield and ultimate strength for longitudinal reinforcement was 78 ksi (538 MPa) and 111 ksi (765 MPa), respectively.

Four small-scale R/UHPC beams were tested. All beam cross sections were 4 in. × 7 in. (10.16 cm × 17.8 cm), and length was 26.5 inches (67.31 cm) (Figure 1). Two beams included four No. 6 (20M) longitudinal bars for a reinforcement ratio, ρ = 9.5% while two beams included two No. 6 (20M) longitudinal bars for ρ = 4.1%. Transverse steel was spaced at either 5.38 inches (137 mm) or 2.69 inches (68 mm), approximately the beam's depth, "d" or half the beam's depth, "d/2." The longitudinal steel, transverse steel, and steel fiber volume fraction for each of the beams are shown in the testing matrix (Table 2).

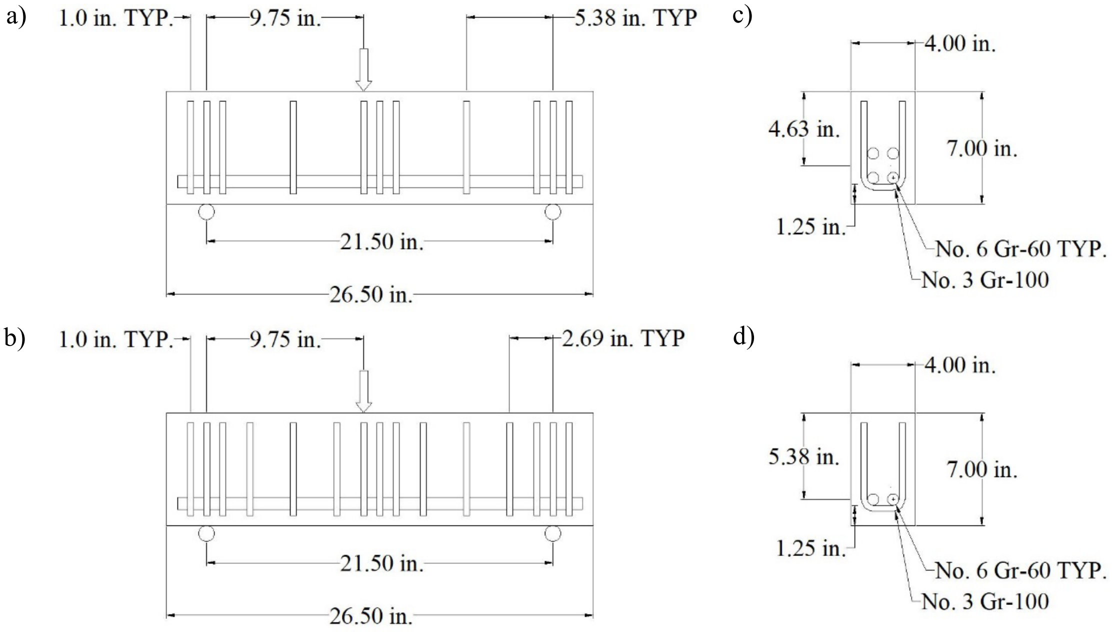

Figure 1: R/UHPC Specimen Design Showing Side View With a) Stirrup Spacing of d, b) Stirrup Spacing of d/2 and Cross-Section With c) ρ = 9.5% and d) ρ = 4.1% (1 in. = 2.54 cm)

All specimens were monotonically tested under three-point loading at 28 ± 2 days. Loading was done slightly off center to drive failure on one particular end of the specimens (Gomaa and Alnaggar, 2019). Shear span-to-depth ratio was designed to be near 2, and was either 1.81 or 2.11, depending on the beam's depth. Testing was deflection-controlled at a rate of 0.1 in./min (2.54 mm/min), and all beams were tested until failure, defined herein as when strength dropped to less than 50% of the peak strength recorded. Crack patterns, type, and width were monitored continuously. Photographs were taken throughout testing.

Table 2: Testing Matrix

Specimen Name	Longitudinal Steel Reinforcement Ratio (%)	Transverse Steel Spacing (in./mm)	Steel Fiber Volume Fraction (%)
UHPC-4.1-d-1	4.1	5.38/137	1
UHPC-9.5-d-1	9.5	5.38/137	1
UHPC-4.1-d/2-0.5	4.1	2.69/68	0.5
UHPC-9.5-d/2-0.5	9.5	2.69/68	0.5

3. Results and Discussion

Load versus drift results for the four specimens are shown in Figure 2. Specimen UHPC-4.1-d/2-0.5 was expected to achieve yield strength prior to failure due to the presence of closely spaced stirrups. During the test, shear cracks began to form near 1.9% drift, but were bridged by the fibers. One shear crack became dominant when it exceeded 0.012 inches (0.3 mm) at 2.1% drift. Strain accumulated at the dominant shear crack through approximately 2.8% drift, however the crack width remained small at the location of the stirrup. Then multiple shear cracks formed and grew while the load carrying capacity diminished almost linearly from a peak value of 53.1 k (236 kN) through failure. Final cracking patterns of each specimen are shown in Figure 3. The test was concluded due to strength loss from a shear fiber bridging failure at an ultimate ductility of 4.7%. Based in the peak load, it appears the longitudinal steel yielded, however the top of the specimen did not experience a crushing failure. Due to its shear response, the specimen was not able to fully utilize the strain hardening capacity of the longitudinal steel to provide additional strength or ductility.

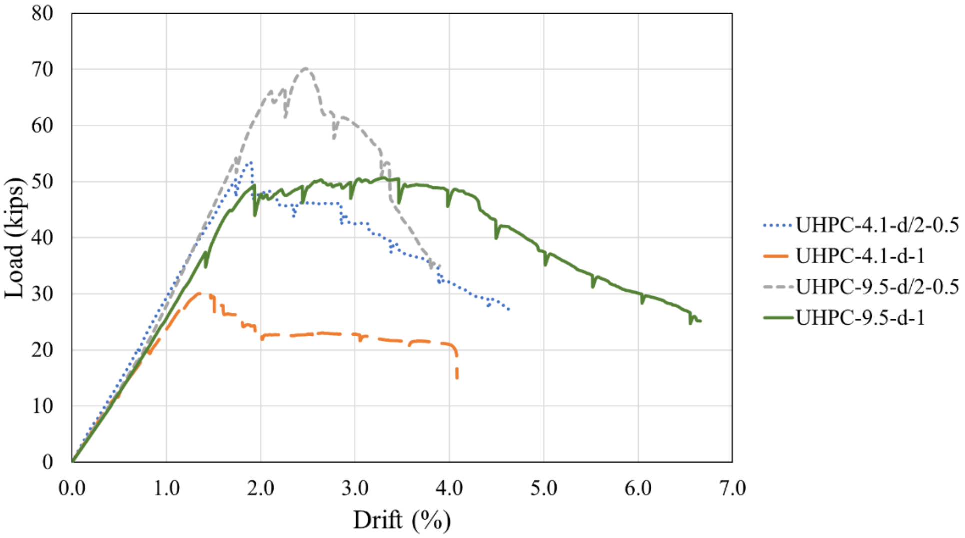

Figure 2: Load Versus Drift Results

With fewer stirrups, specimen UHPC-4.1-d-1 was expected to also fail by shear, but prior to yield. During testing the first shear crack formed at 1.3% drift. By 1.5% drift, fibers began to lose capacity across a dominant shear crack. Authors observed poor consolidation in the corners of this beam, which may have contributed to poor performance and a peak load of only 29.5 k (131 kN) at 1.5% drift. Multiple shear cracks did not form due to the absence of a stirrup to bridge the crack. After 2% drift, significant dowel action kept the specimen's load carrying capacity above 50% of peak until 4.1% drift when the specimen failed.

Specimens with a steel reinforcing ratio of 9.5%, combined with the shear span-to-depth ratio near 2 were expected to drive a high shear demand on the R/UHPC beams. First cracking in UHPC-9.5-d/2-0.5 was a shear crack at 2.1% drift. As deflection increased, flexural-shear, shear cracks, and crushing were noticed. Flexural-shear cracks remained bridged, under 0.008 inches (0.2 mm), throughout the duration of the test, and no spalling due to crushing occurred. A period of pseudo-strain-hardening was most apparent in this specimen, as illustrated by the gain in specimen strength from 64.4 k (286 kN) to 69.6 k (310 kN) between 2.1% and 2.5% drift. One dominant shear crack formed at 3.4% drift after which strength decreased rapidly to failure. This specimen also shows the dominate shear crack width remained small at the location of the stirrup. Based on the peak load, the longitudinal steel did not yield, therefore using 9.5% reinforcement ratio was excessive for this beam's configuration. The presence of crushing indicated the enhanced compression properties of UHPC were utilized. The crushing appeared without significant multiple cracking, thus the ultimate ductility achieved by UHPC-9.5-d/2-0.5, as measured by peak drift, was the smallest of the four specimens at 3.9%.

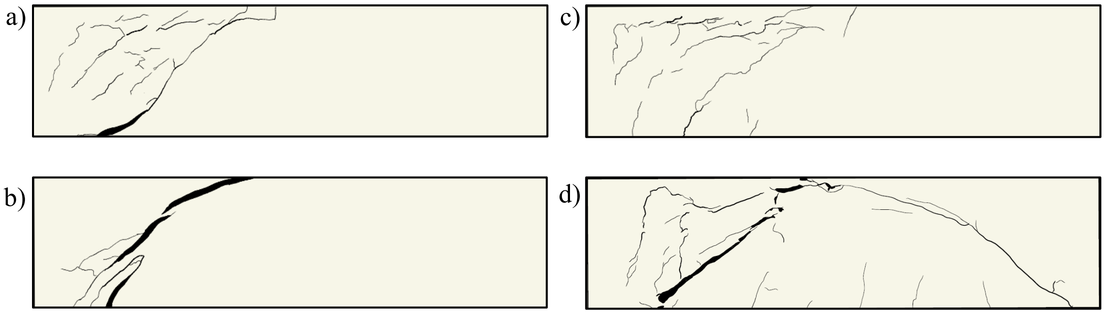

Figure 3: Final Cracking Pattern of a) UHPC-4.1-d/2-0.5, b) UHPC-4.1-d-1, c) UHPC-9.5-d/2-0.5, and d) UHPC-9.5-d-1

The first shear crack formed on both spans at 1.2% drift in specimen UHPC-9.5-d-1. As loading increased, some small flexural and flexural-shear cracks formed, and one shear crack became dominant. The longitudinal bars in UHPC-9.5-d-1 did not yield, and the specimen achieved a peak load of 50.7 k (226 kN), or only 72.3% of UHPC-9.5-d/2-0.5. Comparing the peak strength of the two specimens with 9.5% reinforcement ratio indicates that cutting by half the stirrup spacing was a more effective means of providing shear strength and facilitating load-carrying capacity than doubling the steel fiber content from 0.5% to 1% by volume. The peak strength of UHPC-4.1-d/2-0.5 was 5.6% greater than that of UHPC-9.5-d-1, demonstrating inefficient use of longitudinal steel in specimens with large stirrup spacing. After the peak load, strength remained fairly constant until approximately 4.0% drift then decreased linearly until UHPC-9.5-d-1 failed at 6.7% drift.

Given the relatively short shear span of 9.75 inches (24.8 cm), all beams failed in shear. Beams with a 9.5% steel reinforcement ratio exhibited some flexural or flexural-shear cracking in addition to shear cracking, whereas beams with a smaller reinforcement ratio only exhibited shear cracking. While some crushing was observed, no specimens spalled. Specimens with the closer stirrup spacing provided additional shear capacity and resulted in a higher peak strength in beams at both steel reinforcement ratios included in this study. Ductility of 3.9% drift or higher was achieved by all four specimens tested, indicating that under all combinations of experimental variables in this study, R/UHPC beams maintained good load-carrying capacity under extreme loading conditions.

4. Conclusions

The purpose of this study was to examine the response of R/UHPC beams subjected to a high shear demand due to a relatively low shear span-to-depth ratio and relatively high longitudinal steel reinforcement ratio. Four small scale beams were constructed and experimentally tested at two different reinforcement ratios, two different stirrup spacings, and two different fiber volume fractions. All specimens failed in shear, as expected. Stirrup spacing at approximately half the beam's depth was vital in providing shear strength to delay failure; stirrups controlled shear crack width, facilitated multiple cracking, and enabled yield in the specimen with a 4.1% reinforcement ratio yield. As the reinforcement ratio increased to 9.5%, some crushing was observed and the load carrying capacity dropped prior to longitudinal steel yield. Higher peak strength, and thus, better utilization of tension steel was observed when stirrups were spaced more closely together. The lower fiber volume fraction of 0.5% in specimens with a closer stirrup spacing proved sufficient in providing compression fracture toughness and preventing a crushing failure.

When stirrup spacing was approximately equal to the beam's depth, fewer cracks formed and a dominant shear crack opened sooner in the testing protocol than when stirrups were spaced more closely together. Despite the more dominant shear crack with a larger stirrup spacing, dowel action provided shear capacity and ductility similar to the other specimens. The number of shear cracks decreased and width of the most dominant shear crack increased when stirrup spacing was larger. The larger stirrup spacing, approximately equal to the beam's depth, also corresponded to a 1% steel fiber volume fraction, the larger of the two investigated in this study.

Results in the shear-dominant beams tested herein support a previous finding in flexurally-dominant specimens suggesting that a higher reinforcement ratio more fully utilizes the compression properties of UHPC without producing a crushing failure (Shao and Billington, 2019b). Under the range of variables tested, transverse steel spacing was the most important indicator of peak strength, more so than longitudinal steel reinforcing ratio. These results indicate the importance of stirrups in providing shear strength and more fully facilitating the use of the longitudinal steel properties in tension. Additional investigation should be made into stirrup spacing, transverse steel grade, and UHPC casting direction at relatively large steel reinforcement ratios to further the understanding of shear response in shear-dominant R/UHPC beams.

5. Disclaimer

The views expressed in this presentation are those of the authors and not necessarily reflect those of the United States Air Force Academy, the Air Force, the Department of Defense, or the U.S. Government. PA#: USAFA-DF-2023-221

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