Comparative analysis of confined and unconfined UHPC column under axial loading

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ABSTRACT

This study investigates the use of titanium alloy bars (TiABs) as lateral reinforcement for ultra-high-performance concrete (UHPC) columns. Compared to normal strength concrete, UHPC often requires either a larger quantity of reinforcement or the use of high-grade steel to effectively utilize its superior properties. In this context, this study investigates the use of TiAB for reinforcing UHPC columns due to its high strength, ductility, and excellent corrosion resistance. By introducing TiABs, it is possible to reduce the amount of reinforcement required while still providing effective confinement of the concrete core. In this paper, two UHPC short columns (8 in. × 16 in.) have been investigated, with confined specimens (2% transverse reinforcement) compared against the benchmark or unconfined specimen. The results revealed a significant improvement (29.73% increase) in the compressive strength of UHPC short columns with the use of TiABs as transverse reinforcement.

1 INTRODUCTION

Ultra-high-performance concrete (UHPC), known for its exceptional strength and durability, is a cementitious composite material with discontinuous internal fibers and an optimized gradation of granular materials with a minimum water-to-cement ratio (Hogarth et al. 2023; Wakjira et al. 2024a; Wakjira and Alam 2024a). While confinement models developed for normal strength concrete have been extensively studied, they are not directly applicable to ultra-high performance concrete. This is because UHPC has different mechanical properties, including higher compressive strength, enhanced tensile capacity, and reduced brittleness. In addition, the lateral expansion and confinement effects are more complex in UHPC due to the interaction between the concrete matrix and fibers. Several studies have investigated confinement in UHPC, including external confinement with steel tubes (Guler et al. 2013; Xiong and Liew 2020), fiber-reinforced polymer (FRP) (Çopur et al., 2013; Mander et al., 1988a, 1988b; Razvi & Saatcioglu, 1999; Sharma & Bhargava, 2005), and closed hoops (Empelmann et al., 2008a, 2008b; Shin et al., 2017; Sugano et al., 2007; J. Li et al., 2020; Naeimi & Moustafa, 2021; Yang et al., 2016). The ductility, toughness, and compressive strength of the columns all improved with the use of transverse reinforcement in each of these tests. The challenge to UHPC is its high cost. Thus, several researchers have explored cost-effective UHPC alternatives by replacing part of the cement with silica fume, fly ash, or rice husk ash (Arora et al., 2019; Van Tuan et al., 2011; Wakjira, Kutty, et al., 2024; Yu et al., 2015). These materials not only reduce the overall cost of UHPC but also contribute to sustainability by utilizing industrial by-products and agricultural waste.

Traditional reinforcements often lack sufficient strength and compatibility to fully utilize the superior properties of UHPC. In a machine-learning study, (Wakjira and Alam 2024b) conducted a parametric analysis considering column dimensions, reinforcement ratio, axial load ratio, and material properties as uncertainties. Their findings indicated that UHPC columns showed less vulnerability when reinforced with high-grade rebar. UHPC, with its exceptional strength and ductility, demands reinforcement that can match its advanced mechanical materials. To maximize its full potential, either high-grade reinforcement or a large number of bars should be used. However, increasing the quantity of traditional reinforcement can lead to issues like congestion and reduced constructability. To address this challenge, titanium alloy bars (TiABs) have been used as reinforcement in this study. TiABs have several benefits, like a higher strength-to-weight ratio, excellent corrosion resistance, and good bond performance with UHPC (Acharya 2023; Acharya et al. 2022, 2023; Thapa et al. 2022). Thus, by combining the advanced characteristics of UHPC with the innovative properties of titanium alloy reinforcement, this study aims to study the axial stress-strain response of UHPC confined with titanium alloy bars.

2 CONSTRUCTION AND TEST SETUP

This study consists of two cylindrical UHPC specimens, each measuring 8 inches in diameter and 16 inches in height. One specimen is unconfined (USP) and serves as the benchmark specimen, while the other is a confined specimen (CSP) with 2% of titanium alloy circular ties as transverse reinforcement. In addition, the confined specimen consists of four longitudinal normal steel rebars. The materials utilized in the construction of the column were UHPC, #4 steel bar, and #3 TiAB circular stirrups. Grade 5 smooth TiABs were employed as ties in the column. These TiABs exhibit a yield strength of 958.8 MPa and an ultimate strength of 1032.6 MPa. The modulus of elasticity for TiABs is 106490 MPa (Khadka 2019). The material properties of the TiABs were derived from prior research conducted at Idaho State University.

The mix design for UHPC is shown in Table 1. A high shear mixer was used for the preparation of the UHPC mix using the procedure outlined by Ductal.

Table 1. Mix design of UHPC

Composition	Quantity (in lbs per 50 lb bag)
JS 1000 Grey Premix	50
Water	2.734
Super Plasticizer (Premia 150)	0.683
Steel Fiber (2%)	3.554
Thermal Treatment	No
Volume	0.365 cubic ft/bag

Figure 1. Preparation of UHPC (a) Addition of premix (b) Addition of superplasticizer and water (c) Addition of steel fibers (d) Discharging of UHPC mix (e,f) Preparation of TiAB ties (g) Confined specimen ready for test

After the preparation of UHPC mix, the specimens are placed in a test setup. The schematics of test setup is shown in Figure 2.

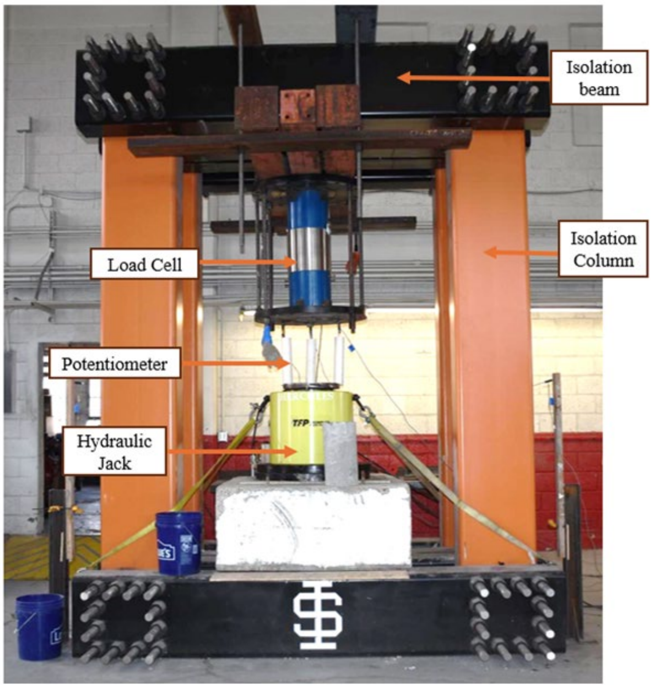

Figure 2. Test setup

3 RESULTS AND DISCUSSION

Monotonic compressive load was applied to the specimens according to ASTM C39 guidelines. A Campbell scientific data acquisition system was used to record the loads during the test. Also, three potentiometers were used to measure the longitudinal deformations. Figure 3 shows the condition of unconfined and confined specimens after the test. It is clear that while unconfined specimen (USP) had brittle failure, CSP showed more ductile behavior.

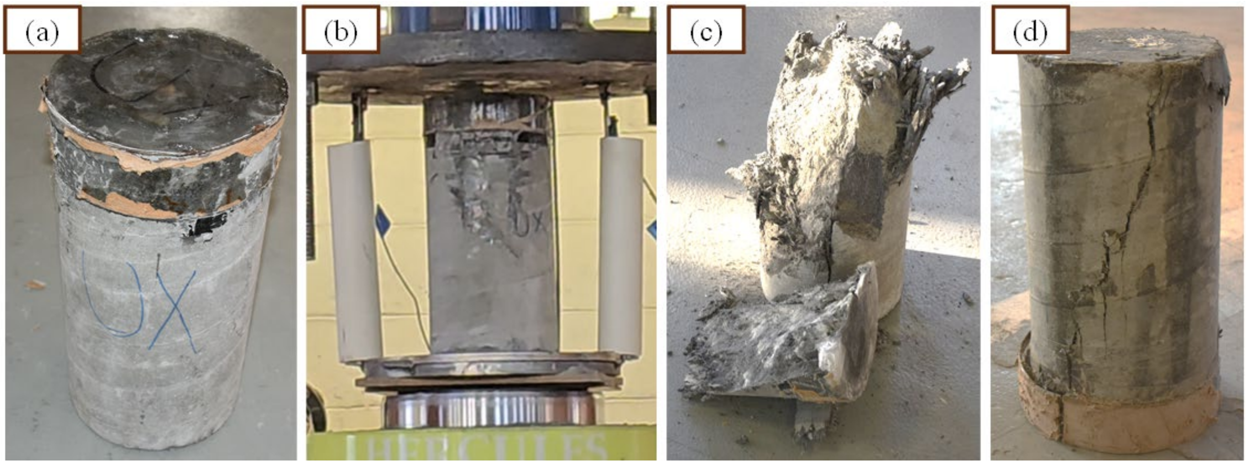

Figure 3. (a) USP ready for test (b) USP placed in the test setup (c) USP after the test (d) CSP after the test

After the test, the deformation measured by the potentiometer was used to obtain the strain, and it was plotted against the axial force recorded by the DAQ as shown in Figure 4. The unconfined specimen (USP) showed the typical behavior of UHPC under compressive loading. Initially, in the elastic region, the concrete deformed in relation to the applied load up to the peak load. Then, when the load was removed, it regained its original position. USP achieved a peak stress of 109.33 MPa at a strain of 0.0054. After the peak, the graph declined after showing ductility. The confined specimen CSP showed the peak stress of 141.84 MPa, which is 29.73% more than the benchmark specimen. In addition, the peak strain and ultimate strain of CSP were 0.0084 and 0.0118, while those of USP were 0.0054 and 0.0074, respectively. Energy dissipation is calculated as the area under the force-displacement curve. Unconfined specimen, USP dissipated 5.75 kJ of energy, while CSP dissipated 13.56 kJ of energy.

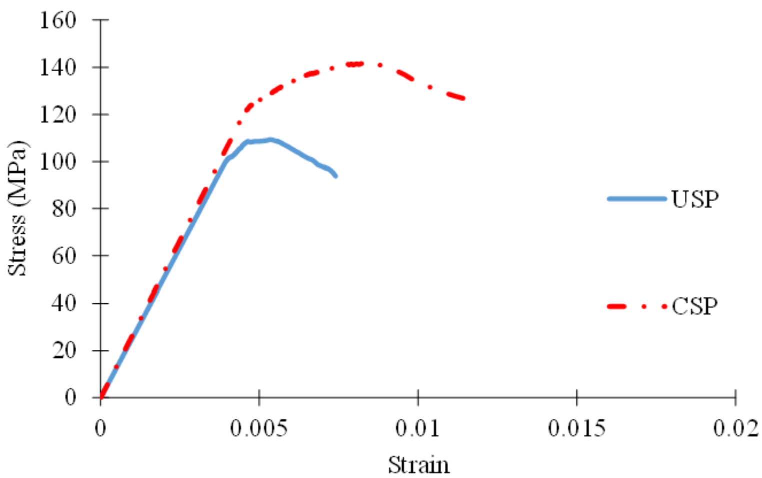

Figure 4. Stress-Strain graph of confined and unconfined specimen

4 CONCLUSION

The stress-strain behavior of UHPC confined by circular titanium alloy hoops was tested. Two specimens were under examination. Unconfined specimen (USP) served as the test specimen and was compared with the confined specimen (CSP). The following conclusions can be drawn from this study:

- Brittle failure mode was observed in the unconfined specimen, which transformed to ductile failure mode in the confined specimen.
- Peak stress of CSP was 141.84 MPa, which is 29.73% more than USP.
- Peak strain increased from 0.0054 in USP to 0.0084 in CSP (55.56% increase). Ultimate strain increased from 0.0074 in USP to 0.0118 (59.46% increase). This increase in peak strain and ultimate strain suggests increased ductility in the confined specimen.

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