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Pullout Behavior of Titanium Alloy Reinforcing Bars in Ultra-High Performance Concrete †

Mahesh Acharya *, Jared Cantrell and Mustafa Mashal

Department of Civil & Environmental Engineering, Idaho State University, Pocatello, ID 83209, USA; cantjare@isu.edu (J.C.); mashmust@isu.edu (M.M.)

* Correspondence: achamahe@isu.edu; Tel.: +1-(980)-339-0764

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Abstract: This paper presents the novel concept of titanium alloy reinforced ultra-high performance concrete (TARUHPC) that can be utilized in bridges. This research highlights the advantages associated with titanium alloy bars (TiABs) and ultra-high performance concrete (UHPC). To validate the concept, pullout tests were implemented to assess the pullout behavior of TiABs with concrete and UHPC. Twelve beam samples (normal concrete and UHPC) were prepared using #6 (ø 0.75 inch) TiABs with different embedment lengths. TARUHPC specimens performed exceedingly better, with an average ultimate force of about 29 kips and a resulting shear stress of 1.82 ksi.

Keywords: UHPC; titanium alloy bars; pullout; durability; concrete structures; bond behavior

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1. Introduction

Recently many advanced novel materials have been introduced into civil infrastructures in order to improve structural performance and durability. Some of these advanced materials that have a huge potential to benefit civil and critical infrastructure include ultra-high performance concrete (UHPC) and titanium alloy bars (TiABs).

1.1. Ultra-High Performance Concrete

Ultra-high performance concrete (UHPC), which is a new class of concrete falling under high-performance fiber-reinforced cement-based composite (HPFRCC) materials, was developed decades ago. A recent study has shown that the research efforts on HPFRCC seismic performance over the past two decades have been increasing every year [1]. The research areas on HPFRCC materials include but are not limited to material testing on beams, columns, structural walls, beam-column joints, and more. UHPC is also considered for rehabilitating bridges and bridge components across the world [2]. UHPC has been utilized in civil infrastructure lately because of its exceptional advantages. It is an advanced cementitious composite material with exceptionally high strength and high durability compared to conventional forms of concrete. The steel fibers in the UHPC concrete restrain the development of cracks and can result in added ductility in structures. UHPC has advantages in many aspects compared to conventional or high-strength concrete, for example, higher compressive and tensile strength, higher elastic modulus, and lower porosity [3].

UHPC has demonstrated its superiority in certain cases, for example, resulting in less maintenance and significantly longer service life due to its better mechanical properties, and the bond performance of the reinforcements embedded in UHPC is critically important for the safety of the UHPC structures. Several investigations are being carried out by researchers across the globe to study the bond behavior of deformed steel bars and UHPC. Graybeal [3], Fehling et al. [4], Holschemacher et al. [5], Saleem et al. [6], Jungwirth and Muttoni [7], and Aryal [8] are among those to study the bond development of steel bar reinforcement embedded in UHPC. It has been found that the UHPC specimens are capable of developing higher bond strengths in bar pullout specimens and are largely dependent on bar spacing, concrete cover, development length, and bar size. It has been evident that compared with normal-strength concrete, the particular material properties of UHPC will inevitably lead to changes in bond properties between rebar and UHPC. The mechanical interlocking between rebar and UHPC is improved due to the material's ultra-high compressive strength and elastic modulus. Bond strength and peak slip have been found to be the key parameters to study the bond behavior between rebar and UHPC.

1.2. Titanium Alloy Bars (TiABs)

Titanium alloy bars (TiABs) are an advanced material that is mostly used in the aerospace industry and has been gaining popularity for applications in concrete structures. TiABs (Ti6Al4V) offer higher strength, superior fatigue performance, high strength-to-weight ratio, lighter weight, lower modulus of elasticity, higher modulus of resilience, reduced rebar congestion, smaller inelastic residual deformation, and excellent corrosion resistance compared to conventional rebars [9]. Presently, TiABs are used to retrofit bridges in the civil engineering industry. They are strong, durable, and naturally resistant to rust and corrosion; however, they cannot be cast like aluminum or iron. This makes TiABs an expensive material compared to steel, stainless steel, aluminum, etc. Several research institutions have carried out studies of TiABs for concrete structures applications, for example, Idaho State University (mechanical properties testing of TiABs [9], bond testing and splicing of TiABs [10], bridge columns reinforced with TiABs [11], cap beam reinforced with TiABs [12]) and Oregon State University (retrofit square column with TiABs [13], retrofit deficient reinforced concrete girders [14]).

The Oregon Department of Transportation (ODOT) and Texas Department of Transportation (TxDOT) have been among the very first to use TiABs for retrofitting bridges in the United States. They have utilized near-surface-mounted (NSM) techniques with TiABs in retrofitting the bridges. TiABs provided increased strength across cracks. Although TiABs are more expensive compared to normal steel rebars, they offer two and a half times higher yield stress compared to grade 60 ksi steel rebars; this results in having less TiABs [15]. Past applications have shown that the use of TiABs provides higher strength and durability at a lower cost and less construction time [14,16]. The use of TiABs for retrofitting bridges offers cost savings for labor and materials, causes less traffic disruption, and provides a durable and accelerated retrofitting process that is competitive to other conventional materials over the service life of a structure. Several DOTs in the United States have adopted TiABs as a retrofitting material for bridges, and the American Association of State Highway and Transportation Officials (AASHTO) recently released a new publication for the use of TiABs [17].

2. Experimental Program

The paper presents the construction and pullout testing of titanium alloy reinforced ultra-high performance concrete (TARUHPC) and compares the performance with titanium alloy reinforced normal concrete (TARNC). A proprietary UHPC that has been common in North America, Ductal JS1000 produced by Lafarge, was selected for the experimental study [18]. The ingredients include dark grey premix (pre-blended cement, sand, ground quartz, silica fume), liquid admixture (high-range water reducer), steel fibers (0.008 in diameter, 0.5 in long), and water. It is claimed by the producer that this type of UHPC provides superior performance in terms of abrasion and chemical resistance, freeze-thaw, carbonation, and chloride penetration. This type of UHPC should be batched in accordance with the Lafarge's Ductal Batching Procedure [19]. Most importantly, high-shear mixers (Figure 1b) are recommended by the producer to properly and efficiently mix the UHPC. UHPC is self-consolidating and should not be vibrated to avoid the segregation of steel fibers. Similarly, a 5000 psi concrete mix with locally available materials (Portland cement, fly ash, fine aggregates, coarse aggregates, and water) was used as the normal concrete to prepare the samples for pullout test.

Figure 1. Construction of TARUHPC specimen: (**a**) batching, (**b**) high-shear mixture, (**c**) discharging UHPC, (**d**) pouring UHPC, (**e**) after pour.

2.1. Test Specimen Preparation

A total of 12 beam samples (six samples TARUHPC and six samples TARNC) of size (22 in × 10 in × 4 in) with different embedment lengths (5 in, 7 in, and 9 in) were prepared and casted for the pullout test. The construction process for TARNC specimens follows the traditional process. However, the preparation and construction process of TARUHPC specimens is slightly different, which is presented in Figure 1.

2.2. Test Setup

The specimens were tested in tension using a displacement-controlled servo-valve-hydraulic actuator. The actuator was supported by a reaction frame. The specimen was supported on two heavy steel blocks. The specimen was then tied to a strong floor using threaded rods bolted down to the strong floor. To tie the TiABs to the actuator head, they were attached to the coupler (ø 2.785 in) using fifteen 0.5 in threaded bolts. The coupler was then tied with the actuator head using four 0.75 in threaded rods and a 1 in thick plate. The loading rate of 0.02 in/min was used to pull the specimen.

2.3. Testing Results

Testing was carried out on a total of 12 specimens, and the summary of pullout testing is presented in Table 1.

Table 1. Pullout testing results.

	TARUHPC			TARNC		
Embedment Length, l (inch)	5	7	9	5	7	9
Average Ultimate Force, P (kip)	26.2	30.0	30.6	5.4	4.9	4.7
Average Slip at Ultimate Force (inch)	0.036	0.045	0.044	0.0025	0.0019	0.0027
* Shear Stress, τ (ksi)	2.22	1.82	1.44	0.46	0.30	0.22

* Note: Shear Stress ($\tau = P/\pi d l$); d = diameter of bar; 1 in = 25.4 mm; 1 kip = 4.45 kN; 1 ksi = 6.89 MPa.

3. Discussion

The next generation novel concept titanium alloy reinforced ultra-high performance concrete (TARUHPC), which is a combination of titanium alloy bars (TiABs) and ultra-high performance concrete (UHPC), has great potential for civil infrastructures. Pullout testing results showed improved performance of the TARUHPC compared to the TARNC, as shown in Table 1. For the test setup provided, the TARNC had a premature failure with an average ultimate force of about 5 kips and a resulting shear stress of only 0.33 ksi. However, TARUHPC performed exceedingly better, with an average ultimate force of about 29 kips and a resulting shear stress of 1.83 ksi. To ensure that TARUHPC can be structurally efficient to be used in civil infrastructures, small-scale experiments on structural elements, such as beams and columns, should be carried out. There is presently little to no data on testing of the TARUHPC on structural elements. Researchers at Idaho State University are currently working on an effort to test the TARUHPC concept on structural elements and are even utilizing various artificial intelligence (AI) tools to evaluate the performance of the TARUHPC concept.

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