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Comparative Pull-Out Testing of Bars Used in NSM Strengthening: Preliminary Study

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Abstract **-** The near-surface mounted (NSM) technique is a widely recognized method for strengthening reinforced concrete (RC) structures. While carbon fiber-reinforced polymer (CFRP) bars are commonly used due to their high tensile strength and corrosion resistance, titanium alloy (TiA) bars offer a promising alternative where enhanced ductility and durability are required. This study presents preliminary observations from a direct pull-out test of TiA bars embedded in concrete using the NSM method. Differences in failure behavior were noted, offering insight into the mechanical interaction between reinforcement and adhesive. The findings are part of an ongoing study evaluating the feasibility of using TiA bars in NSM applications. These findings highlight the potential of TiA bars as a resilient and durable alternative to CFRP in NSM strengthening applications.

Keywords**:** Titanium alloy bars, near-surface mounted, slip, preliminary testing, pull-out test

1. Introduction

The structural performance of reinforced concrete (RC) structures tends to deteriorate over time due to reinforcement corrosion, environmental exposure, increased service demands, and seismic activities [1]. Among the various strengthening techniques, near-surface mounted (NSM) reinforcement has gained substantial recognition for its effectiveness in enhancing the structural performance of RC members. In this method, reinforcement bars or strips are embedded into grooves cut into the concrete cover and bonded using a suitable adhesive [2]. Compared to externally bonded reinforcement, NSM systems offer superior bond characteristics, improved durability, and enhanced protection against environmental degradation [3], [4].

Carbon fiber-reinforced polymer (CFRP) bars are commonly used in NSM applications due to their high tensile strength, lightweight nature, and resistance to corrosion [5]. However, their linear-elastic behavior until failure and low ductility significantly constrain their performance in demanding structural environments.

Titanium alloy (TiA) bars have recently emerged as a promising alternative to conventional reinforcement materials in NSM strengthening systems. TiA exhibits a favorable combination of high specific strength, exceptional corrosion resistance, and significantly greater ductility compared to CFRP bars [6], [7]. Experimental investigations conducted at Oregon State University have examined the application of TiA bars in NSM systems for the shear and flexural strengthening of RC girders, demonstrating promising structural performance [8], [9]. More recently, research at Idaho State University has focused on assessing the feasibility of using TiA bars in the construction of resilient and durable RC structures, particularly for use in aggressive environments and seismic-prone regions [10], [11].

To the authors' knowledge, no prior study has directly compared the bond performance of TiA and CFRP bars in NSM applications. Existing studies on NSM TiA bars have shown that failure is typically governed by the adhesive–concrete interface or by the tensile capacity of the surrounding concrete, rather than by yielding of the TiA bars [12]. Although modifications such as the use of hooked bar ends have been found to enhance stress transfer and improve bond capacity, the average stress levels in TiA bars at failure remain below their yield strength [8].

This paper presents a preliminary comparison of two representative pull-out specimens, one using a TiA bar and the other a CFRP bar, as part of an ongoing program at Qatar University aimed at evaluating the potential use of TiA bars for NSM flexural strengthening of RC beams.

2. Experimental Program and Specimen Configuration

This paper presents the results of two representative pull-out specimens selected from a broader experimental program, designed to evaluate the bond performance of NSM TiA bars. Each specimen consisted of a C-shaped concrete block cast from normal-weight concrete with a target compressive strength of 50 MPa. The external dimensions of the blocks were 300 mm × 200 mm × 300 mm, with an internal opening of 180 mm × 90 mm. A central square groove measuring 25 mm × 25 mm was cut along the height of each block to accommodate the NSM bar. For both specimens, a bonded length of 12 times the nominal bar diameter (12 d_b) was used.

The pull-out tests were performed using a custom-built steel test frame, as illustrated in Figure 1. Bar slip was recorded at both the loaded and free ends using linear variable differential transducers (LVDTs), and all measurements were captured via an automated data acquisition system.

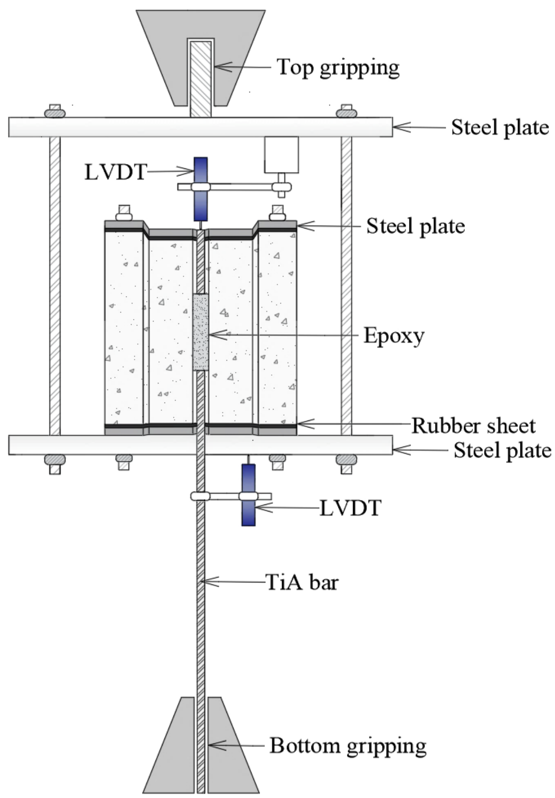


Fig. 1: Schematic of the pull-out test setup

The TiA bar used in the test was fabricated from Grade-5 Ti-6Al-4V alloy, with a nominal diameter of 10 mm, a modulus of elasticity of 103 GPa, and a yield strength of 971 MPa. The CFRP bar had the same nominal diameter, a modulus of elasticity of 120 GPa, and an ultimate tensile strength of 1800 MPa.

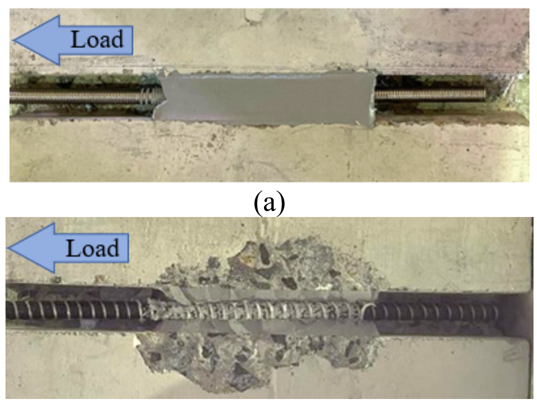
3. Test Results and Discussion

Table 1 provides selected test parameters, including the maximum pull-out load (P_{max}), the maximum loaded-end slip (s_l) corresponding to P_{max}, and the observed failure mode.

Table 1: Summary of observed behavior in two representative specimens.

Specimen	P_{max} (kN)	s_l (mm)	Failure mode
TiA specimen	66.9	10.9	Bar yielding followed by pull-out
CFRP specimen	95.6	2.9	Epoxy cover splitting

The TiA specimen exhibited bar yielding before pull-out, indicating effective load transfer and full utilization of the bar's tensile capacity, as illustrated in Figure 2a. In contrast, the CFRP specimen failed in a brittle manner through explosive splitting of the epoxy cover and partial concrete detachment along the bonded length, as shown in Figure 2b. **As shown in**



(a)

(b)

Fig. 2: Failure modes observed in (a) TiA specimen and (b) CFRP specimen.

Figure 3 shows a representative load–slip response at the loaded end for TiA and CFRP specimens. The TiA specimen exhibited a bilinear curve, with an initial linear part representing elastic behavior, followed by a plateau indicating yielding and plastic deformation of the TiA bars. In contrast, the CFRP specimen showed a noticeably stiffer response due to its higher elastic modulus and failed abruptly, as indicated by a sudden load drop caused by epoxy cover splitting and concrete detachment. Notably, the CFRP specimen achieved a maximum pull-out load higher than that of the TiA specimen.

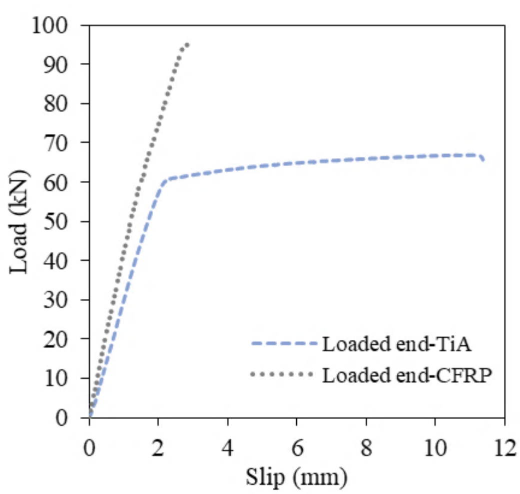


Fig. 3: Load–slip response at the loaded end for TiA and CFRP specimens.

4. Conclusion

This brief paper presents preliminary results from two representative pull-out specimens as part of a broader experimental program investigating the bond behavior of TiA bars in NSM strengthening applications. A comparative evaluation with CFRP bars was conducted through direct pull-out testing. While the CFRP bar exhibited a higher maximum pull-out load, its brittle failure—characterized by epoxy cover splitting and concrete detachment—highlights its limited energy dissipation capacity. In contrast, the TiA bar demonstrated a more desirable ductile response, with clear yielding followed by pull-out, indicating effective bond development and utilization of its tensile capacity.

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