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Pull-out performance of GFRP bars in gypsum: Laboratory and field investigation

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ABSTRACT: The growing demand for permanent reinforcement systems for unstable rock masses, ensuring high reliability in terms of mechanical performance and long-term durability, is a widely discussed topic in the geotechnical field. Galvanized or steel bars are the most commonly used materials for anchors in these applications; however, they are prone to corrosion. In aggressive environments characterized by high humidity or continuous water seepage, stainless steel bars are often used, despite their significantly higher cost. In this context, Glass Fiber Reinforced Polymer (GFRP) bars offer an attractive alternative due to their inherent corrosion resistance, high tensile strength, and lightweight properties. This study investigates the tensile behaviour of GFRP bar nails embedded in gypsum rock, a material often prone to instability and mechanical degradation. Extensive pull-out tests were conducted under both laboratory and field conditions to evaluate the mechanical performance and bond strength between the GFRP bars, the grout material, and the gypsum matrix. Particular attention was given to the development and optimization of test instrumentation, ensuring perfect axial force transmission, high-quality data acquisition, and enhanced reliability of experimental outcomes. The results of the experimental campaign are presented and discussed in detail, with a focus on the performance of GFRP nails using two different grout materials: resin and cement. The findings highlight the potential of GFRP nails as a cost-effective and durable solution for reinforcement systems, particularly in highly aggressive environments where traditional materials are prone to premature failure.

KEYWORDS: rock reinforcement, fiberglass, instability.

1 INTRODUCTION

The stability of rock masses particularly those comprising soft or evaporitic lithologies has long presented a challenge for geotechnical and structural engineers. In such settings, long-term reinforcement systems are often required to mitigate the risk of collapse, particularly in areas with significant anthropogenic or infrastructural relevance. Traditional reinforcement systems typically rely on metallic bars such as steel rods, which offer high stiffness and tensile strength. However, these materials are susceptible to corrosion in aggressive environments, such as those with high humidity, water ingress, or sulphate exposure (Manquehual et al., 2021). Although stainless steel provides improved corrosion resistance, its elevated cost restricts its widespread use.

As a viable alternative, Glass Fibre Reinforced Polymer (GFRP) bars have gained attention due to their superior corrosion resistance, high specific strength, lightweight nature, and relative ease of handling and installation (Alves et al., 2011; Wang et al., 2018; Sandrini et al., 2022). Despite their increasing popularity in concrete structures, the application of GFRP bars in rock reinforcement remains less established, particularly within the context of soft and porous rocks like gypsum. In such materials, the mechanical interaction between the bar, grout, and host rock is critically dependent on interfacial properties, surface preparation, and grout type (Baena et al., 2009; Sandrini et al., 2023).

To address this gap, the present study investigates the tensile behaviour of GFRP bar anchors embedded in gypsum, examining both epoxy resin and cementitious grouting options. The newly developed field-testing apparatus and laboratory testing frame have permitted to quantify bond strength, load transfer mechanisms, and failure modes of GFRP bars in gypsum. Instrumentation was optimised for precise axial load application and more accurate data collection. By comparing two grouting materials, this research aims to evaluate the feasibility of GFRP bars as a durable, cost-effective reinforcement solution for gypsum-based rock masses in challenging geotechnical environments.

2 LABORATORY TESTS

To evaluate the performance of GFRP bars anchored in soft rock, a series of pull-out tests were carried out on specimens extracted from the Santa Brigida gypsum formation located in Northen Italy. These tests were performed using a newly designed laboratory pull-out apparatus, developed by modifying an existing Unitronic S206M testing frame by Matest spa (www.matest.com) and full details can be found in Sandrini (2025). The original machine, intended for steel bar testing, was re-engineered both mechanically and via bespoke software to allow precise axial load application, real-time data acquisition, and simultaneous integration of external LVDT sensors. The upgraded system includes a self-tightening wedge-based clamping mechanism for smooth GFRP bars, an adjustable base for different sample heights, and a 3D-printed fixture supporting three LVDTs mounted 120° apart to measure the true displacement of the bar relative to the rock surface (Figure 1).

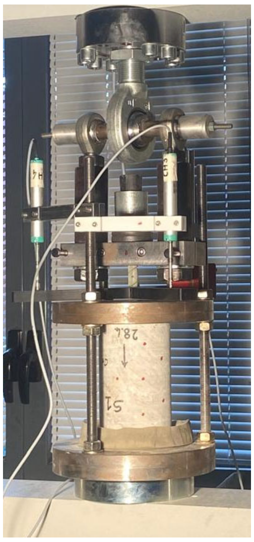


Figure 1. Laboratory test layout, showing the bar blocking system, the reaction frame and a Gypsum's sample during a pull-out test.

10 cm diameter cylindrical gypsum specimens were prepared with a central 18mm diameter hole to accommodate 12mm diameter GFRP bars. The grout used was MasterRoc MP 368 resin, selected for its high mechanical strength ($\tau_{res} \approx 9$MPa) and excellent adhesion properties, which make it particularly suitable for bonding in relatively smooth and low-porosity substrates such as gypsum. Furthermore, MP 368's fast curing characteristics and compatibility with in-situ conservation needs (due to its injectability and chemical stability) make it an ideal grout material in heritage-sensitive geological materials. These attributes are critical in conditions where reliable anchorage is required without extensive surface modification or prolonged curing.

Table 1. Pull-out test results of GFRP bars fixed with resin in gypsum's samples from Santa Brigida cave.

ID test	$L_{anchor/hole}$	D_{hole}	D_{bar}	Breaking Force	τ_{lim}
	[mm]	[mm]	[mm]	[N]	[MPa]
S1-GY	70	18	12	9.7	2.45
S1-GY	100	18	12	15	2.65
S1-GY	130	18	12	20.5	2.8

Anchor embedment lengths varied among the specimens (70mm, 100mm, and 130mm for S1-GY, S2-GY, and S3-GY, respectively), as detailed in Table 1. The samples were left to cure for a standardised period to ensure consistent bonding. After curing, pullout tests were carried out at a constant displacement rate of 0.25mm/min, with data acquisition at 3Hz. The displacement readings obtained from the three external LVDTs were corrected for bar elongation and system compliance, allowing for accurate determination of the pure anchor displacement at the rock face (Figure 1).

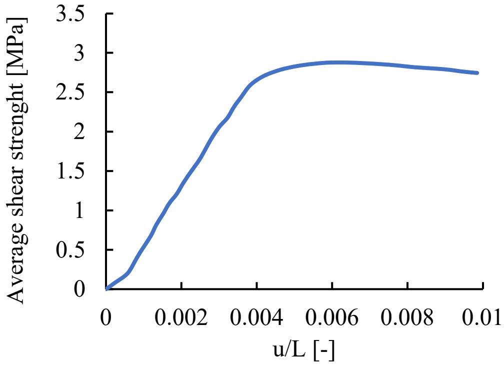


Figure 2. Mean shear strength vs. normalised displacement

A typical pullout test result is shown in Figure 2. All tests revealed consistent failure along the interface between the resin and the gypsum, with τ_{lim} values averaging around 2.6 MPa. Despite the high intrinsic strength of the resin, the lower-than-expected anchorage performance is attributed to surface factors: drilling into gypsum generates a layer of fine powder that may inhibit proper adhesion, and the rock's low porosity along with the very smooth surface limits mechanical interlocking. These findings underscore the importance of surface preparation in anchorage efficiency and validate the use of laboratory-prepared untreated surfaces to simulate realistic field conditions.

3 FIELD TEST CAMPAING

3.1 *Field test location and anchors characteristics*

Within the former gypsum extraction site of Santa Brigida (BG), which in recent years has experienced numerous collapses endangering part of the overlying residential area (Castellanza et al 2008), comparative pull-out tests were conducted on anchors equipped with Ø25 mm GEWI bars (as specified in the executive safety project for cavity stabilisation) and anchors using Ø25 mm GFRP (Glass Fibre Reinforced Polymer) bars (see Table 2). To this end, a specific wall within the mine was identified where, under fully safe conditions, it was possible to install the test anchors. This location was carefully selected to ensure optimal conditions for the execution of the tests. The adopted safety measures ensured that all testing activities could be carried out without risk to personnel or equipment (see Figure 3).

Figure 3. Wall with anchors in Santa Brigida cave.

Table 2. GEWI and GFRP bar details.

Type	Diameter	Guaranteed Tensile Strength	Yield load	Tensile force	E
	[mm]	[MPa]	[kN]	[kN]	[GPa]
GEWI	*25*	*550*	*330*	>300	205
GFRP	*25*	*800*	-	>392	46

The GFRP bars were equipped with a threaded steel head bonded to the bar with epoxy resin over a length of one meter. This was done to enable the attachment of the load during the pull test using a simple nut. The materials and dimensions of this anchoring system were tested in the laboratory by the supplier to ensure a grip that exceeds the breaking strength of the bar itself. In terms of grouting materials, an MP368 polyurethane resin and a simple cement grout made with 32.5 R cement mixed with water in a 1/2 ratio were employed. The drilling was carried out using a Jumbo drill rig. The holes were made with a diameter of 36 mm for bars grouted with resin and 51 mm for those installed with cement grout. Grout injection was performed through mixing pumps via small tubes placed inside the hole along the bars.

Table 3. Anchors specimens' details of Santa Brigida field test.

ID test	Bar type	Grout type	Hole Diameter	Bar Length	Bar Diameter
		[MPa]	[mm]	[mm]	[mm]
GFRP1	*GFRP*	*Resin*	36	1000	25
GFRP2	*GFRP*	*Resin*	36	1000	25
GFRP3	*GFRP*	*Resin*	36	3000	25
GFRP4	*GFRP*	*Cement*	52	3000	25
GFRP5	*GFRP*	*Cement*	52	1000	25
GEWI1	*GEWI*	*Resin*	36	3000	25
GEWI2	*GEWI*	*Resin*	36	1000	25
GEWI3	*GEWI*	*Cement*	52	3000	25
GEWI4	*GEWI*	*Cement*	52	1000	25

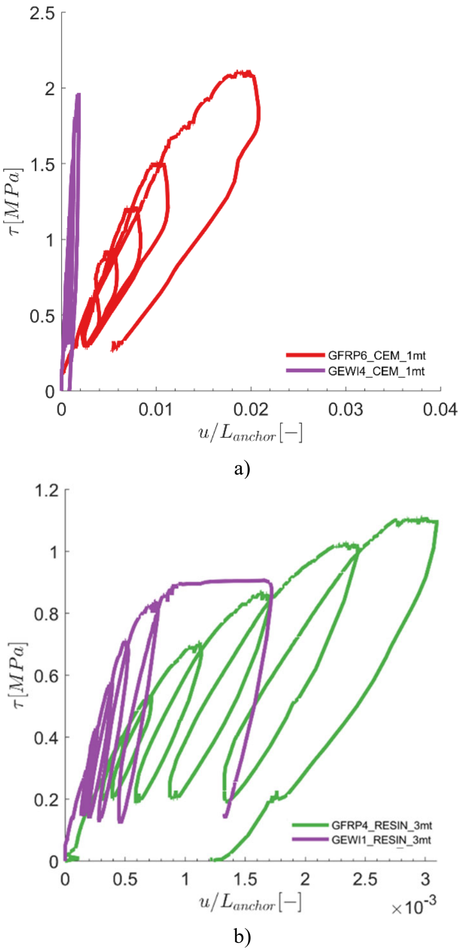
All the holes were drilled to a length of 3 meters, and the bars listed with a length of 1 meter were wrapped with tape for the first two meters before being inserted into their respective holes and grouted. This taping was done to isolate the section of the bar in contact with the cement, allowing the examination of only the tensile strength of the last meter of the bar at the bottom of the hole.

3.2 *Pull-out Field-testing device*

To enhance the reliability and precision of GFRP pull-out tests in medium to hard rock, a refined version of the most common testing system (ASTM D4435, 2014) was used. A key modification introduced is the incorporation of a hollow spherical joint, allowing self-alignment between the hydraulic piston and the bar, thereby ensuring that axial loads are applied concentrically hence mitigating the influence of eccentric forces. The bearing plate was also redesigned with a central opening to allow direct visual inspection of the bar-rock interface throughout the test, enabling detection of any early failure indicators or bar movement at the surface. To improve displacement monitoring, three LVDTs were mounted directly onto the free section of the GFRP bar, just outside the rock surface. These were arranged 120 degrees apart using a custom 3D-printed support system, ensuring localised, multi-directional displacement readings. An additional LVDT was positioned adjacent to the bearing plate to monitor potential displacements or deformations in the rock mass itself. Furthermore, a pressure transducer was installed to record hydraulic pressure in real time, adding an additional control layer to safeguard against overloading and to support the accurate interpretation of load–displacement behaviour. The alignment between the piston, load cell, and spherical joint was ensured by a custom centring device integrated into the load cell structure. This centring system guaranteed effective axial contact and minimised test artefacts related to misalignment. All measurements were synchronised and recorded using the cyber-plus 8 progress acquisition system by Matest spa, capable of capturing high-resolution data across multiple channels.

4 FIELD TESTS RESULTS

Figure 4 shows some of the pull-out curves of the tests listed in Table 3. The results demonstrate that GEWI bar nails exhibit significantly higher stiffness compared to GFRP bar nails, which instead display a more elastoplastic behaviour regardless of the grouting material used (Figure 4). The tests conducted, using GFRP bars and the steel GEWI bars grouted with cement mortar, did not show significant differences between them. Due to their different stiffness (Table 2), for safety reasons, only the GFRP bars were brought to failure, while the GEWI bars were stopped just below their yield limit (around 330kN). As shown in Table 4, none of the tests resulted in failure of the interface; only the bars themselves reached failure.



a)

b)

Figure 4. Curves comparison for a) 1m cement installed and b) 3m resin installed, GFRP and GEWI bars.

Table 4. Tests details and results obtained.

ID test	Max force reached	τ_{lim} * (interface rock/grout)	Comments
	[kN]	[MPa]	
GFRP1	500	>1.47	Bar breakage
GFRP2	490	>4.33	Bar breakage
GFRP3	460	>4.06	Bar breakage
GFRP4	430	>2.68	Bar breakage
GFRP5	450	>0.94	Bar breakage
GEWI1	306	>0.91	Safety stop
GEWI2	309	>2.73	Safety stop
GEWI3	340	>2.12	Safety stop
GEWI4	308	>0.64	Safety stop

*Maximum value reached during the test

5 CONCLUSIONS

This study evaluated the pull-out performance of Glass Fibre Reinforced Polymer (GFRP) bars embedded in gypsum rock through a combined laboratory and field investigation, supported by an extended analytical model. Laboratory tests, conducted on small-scale cylindrical specimens with short anchorage lengths, showed failure consistently occurring at the grout-rock interface. The recorded average shear strength values (~2.6MPa) were found to be governed primarily by the surface condition of the drilled hole and the mechanical properties of the gypsum, rather than the capacity of the GFRP bar or the grout itself. In the laboratory, shorter embedded lengths (e.g., 70-130mm) resulted in relatively low ultimate loads, as expected, with failure governed by bond mobilisation over the available surface area. In contrast, field tests involving longer bars (up to 3 metres) demonstrated significantly higher pull-out resistance, with failures occurring by bar rupture rather than interfacial debonding indicating that full bond strength had been mobilised across the extended anchorage zone.

The field results further confirmed that GFRP anchors exhibit an elasto-plastic load-displacement response, in contrast to the stiffer, linear-elastic behaviour of GEWI steel bars. The lower stiffness of GFRP ($E \approx 46$GPa vs. 205GPa for steel) results in increased deformation capacity, which can be advantageous in dissipating energy and accommodating differential movements in weak rock masses.

In summary, the findings confirm that GFRP anchors, when properly designed with adequate embedment length and grout selection, represent a durable and efficient alternative to traditional steel systems. Their corrosion resistance, high strength, and ductile failure behaviour make them particularly suitable for aggressive, moisture-sensitive, or conservation-critical environments. Future work should focus on long-term monitoring, cyclic loading behaviour, and further optimisation of grout–bar configurations for site-specific conditions.

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