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GFRP Pipe for Tunnel Face Reinforcement: The Laboratory Characterization

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3. Conventional Tunnelling Methods in Development and Use

Summary

In tunnelling engineering the preliminary support of the tunnel face is often based on the soil nailing technique, considered as one of the most effective provisions for the control and reduction of the tunnel pre-convergence and face extrusion. The nails are mostly made of Glass Fibre Reinforced Polymer (GFRP), due to the advantages this material offers in this application. In the years, improvements have been introduced also in the theoretical and computational analysis of nailing systems, so that nowadays it is possible to take into account their mechanical action at the design stage. The nail performance being a key design parameter, an accurate investigation on the mechanical response of the GFRP pipe and on the pipe-soil interaction is therefore fundamental to support specific design assumptions. Moreover, the correct identification of the associated mechanical parameters, such as the pipe tensile strength and the pipe-soil bonding adherence, is required to limit the uncertainties in the values adopted in the design. In this paper the attention is focused on laboratory tests carried out for this characterization. The principal objective is to set up appropriate procedures to characterize GFRP pipes for soil nailing systems, that ensure reliability and repeatability of the tests. The result is a series of recommendations specifically addressed to adapt ordinary tensile and pull out tests to the treatment of GFRP pipes.

***Keywords**: Excavation Reinforcement, GFRP pipe, Soil nailing, Pull out test, Tensile test, Laboratory test*

1. Introduction

The soil nailing is one of the most effective provisions for the control and reduction of the pre-convergence and face extrusion of tunnels driven in difficult ground conditions and its use has become integral part of modern design methods [1,2,3]. In the years, improvements have been introduced in the technological aspects concerning the production and installation of the nails, and efforts have been made to better understand the mechanical behaviour of new materials and equipment.

These efforts were basically devoted to observe and characterize the mechanical response of pipes subjected to unconfined traction, to identify the material tensile strength, and of grouted pipes subjected to a pull out action, to identify the bonding effect between the pipe and the surrounding ground mass or grout. The former requires theoretically a simple laboratory equipment, although pipes made of particular materials, such as the Glass Fibre Reinforced Polymer (GFRP), require suitable procedures in order to prevent undesirable effects or damages to the pipe, that would lead to unreliable results. The pull out tests can be performed both in the laboratory and on site, in the first case taking advantage of ideal and repeatable testing conditions, in the second case allowing for a characterization of the nail response in the real and most representative ground conditions.

Limiting this investigation to laboratory tests, the need rises to define specific procedures and equipments that ensure, from one side, an accurate identification of the mechanical parameters considered as key factors in nailing systems and, from the other, the avoidance of undesirable collateral effect on the pipes under testing.

The principal objective is therefore to set up appropriate procedures for the characterization of GFRP pipes for soil nailing systems, that ensure repeatability of the tests and reliability of the results. The attempt is to suggest a series of practical recommendations, aimed at adapting procedures and equipment for the conventional laboratory testing, such as tensile and pull out tests, to the treatment of GFRP pipes.

2. The soil nailing by Glass Fibre Reinforced Polymer pipes

The use of pipes made of Glass Fibre Reinforced Polymer (GFRP) in soil nailing represents advantages due to the characteristics of this material: the GFRP offers low unit weight and high resistance to corrosion, and the uniform distribution of aligned glass fibres obtained during the "pultrusion" manufacturing process [4,5] can ensure a high tensile strength of the pipe. In addition, GFRP pipes can be easily cut, a property particularly relevant in the reinforcement of tunnel faces, where the removal of the already nailing stabilized ground mass has to take place during the tunnel advance. The soil nailing by GFRP pipes offers high versatility and it is therefore very effective in applications where length, number and pattern of nails have to be quickly modified to adapt to the sudden changes of ground conditions, such as in tunnelling.

The key mechanical properties of soil nails are basically the pipe tensile strength and the shear strength at the pipe-soil interface, also referred to as pull out resistance. These properties are involved in the mechanical principle on which the soil nailing technique is based, that is the activation of tensile forces within the pipe, due to the surrounding soil movements (i.e. the tunnel face extrusion), which are transferred to the ground by friction along the interface. The mechanical effect on the surrounding ground mass is therefore an increase in its apparent cohesive strength. In grouted nails, an additional effect is given by the injection pressure reached during the nail grouting: if sufficiently high, this pressure exerts a confinement on the ground, thus increasing its effective shear strength.

Both properties, i.e. the tensile strength and the pull out resistance, are used to predict the performance of the nail and to take into account the mechanical action of the soil nail system at the design stage. They can be assessed by laboratory and field tests. The former are meant to identify the tensile strength and the interaction between the pipe and the injection mixture, and the possibility to carry out tests under controlled and repeatable conditions represents the basis for the commercial certification of the product. The laboratory pull out test is probably the most convenient and widely used technique for assessing the interface shear strength, though not the only one [6]. It allows to highlight the different performance of different nail types under the same working conditions, and the relevance of various influence factors.

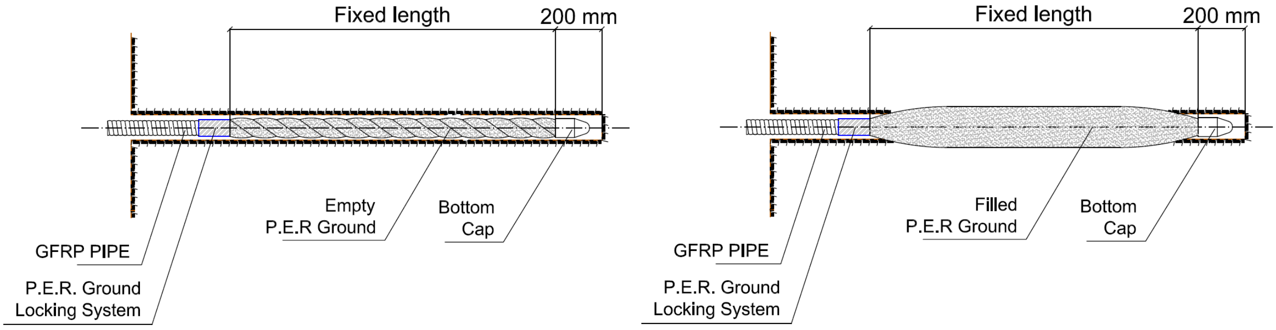
The interface shear strength should be identified also by field pull out tests, due to the great influence of the actual on site conditions on the bond properties [7,8]. In general, field pull out results cannot be straightforwardly extended to different sites and specific field testing programmes should be always planned to assist every new design.

The pipe tensile strength depends on the content of longitudinal continuous glass fibres, usually expressed as percentage by weight or volume of fibres with respect to the total weight or volume of the pipe. In particular, a higher tensile strength is associated with a higher content of fibres, according to a relation that can be assumed as approximately linear.

Although the resistance to pull out is influenced by factors related to the ground conditions, in general a better performance is reached when the surface of the pipe is treated so to improve the lateral adherence. Instead of etching a groove along the surface, which cuts part of the external glass fibres and therefore reduces the tensile strength, a new manufacturing process has been patented, in which a corrugated profile is created by preforming the aligned glass fibres before the polymerisation of the resin (VTR-CRG pipe, by Elas Geotecnica S.r.l.). This new product, while maintaining a high tensile strength, offers a pull out resistance that proved to be higher than the one offered by standard improved GFRP pipes under the same testing conditions [9]. The reason stems from the different mechanical interaction at the interface, highlighted by the fracture pattern observed after the complete pull out of the pipe: while in the case of standard pipe the fractured zone is narrowly localized around the pipe surface, with the corrugated pipe the fractures extend over a larger volume, thus proving the occurrence of an interlocking mechanism that induces positive compressive stresses around the pipe and eventually a higher pull out resistance.

In standard grouted soil nails the GFRP pipe is inserted in a borehole and grouted with a low pressure injection. An improved soil nail is produced (PERGround, by Elas Geotecnica S.r.l.), in which an external expandable geotextile sheath wraps the GFRP pipe for the whole of its length and is sealed at head and tip (Figure 1). A low shrinkage cement grout is injected through a small tube between the pipe and the sheath, so that the sheath inflates until filling the borehole. The sheath is devised to contain the grout and it allows for high pressures of injection, preventing fracturing and consequent grout dispersion. The result is a homogeneous reinforcing bar, characterized by a uniformly distributed adherence.

In all the field tests carried out on traditional and improved soil nails under the same site conditions, the improved nails exhibited a pull out resistance higher than the one measured on standard nails, and in some cases up to 10 times higher [10]. As an example, Figure 2 reports the results obtained from on site pull out tests on various GFRP nail types: the standard profile pipes, the corrugated profile pipes VTR-CRG, and the PERGround nails in which corrugated profile pipes were used. The results confirm the better performance of corrugated pipes with respect to standard ones also in field conditions. In this case, they offered pull out loads approximately 8 times greater than those offered by standard pipes.



(a) (b)

Fig. 1 *Improved soil nail: (a) before and (b) after grout injection (PERGround, Elas Geotecnica S.r.l.)*

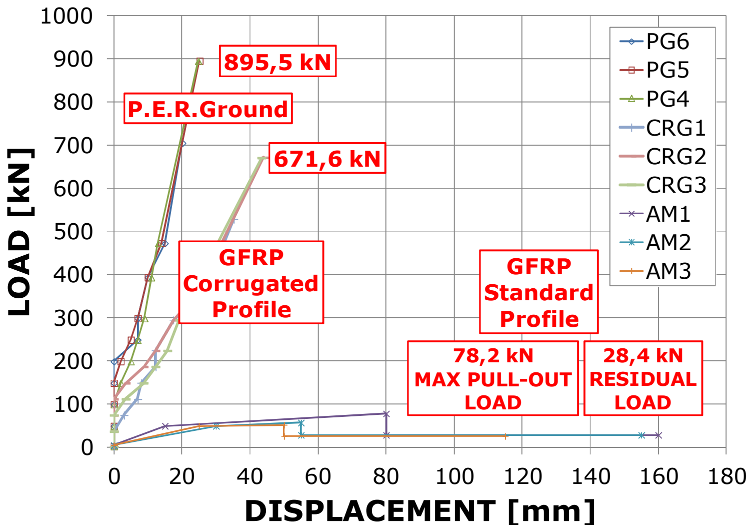


Fig. 2 *Results of on site pull out tests on standard GFRP pipes (AM), corrugated GFRP pipes (CRG) and innovative PERGround nails (PG)*

Moreover, a large additional enhancement in the nail performance is obtained with PERGround nails which result in an increase of pull out load of about 33% with respect to the same corrugated profile pipe used with a conventional installation. This effect is likely due to the higher injection pressures that can be applied during grouting, due to the presence of the external sheath. In particular, in the case under consideration, injection pressures up to 15 bars were applied, while in the conventional soil nail the maximum pressure was limited to 3 bars to prevent soil fracturing. The consequent high adherence, uniformly distributed along the pipe-soil interface, led to the high pull out resistance reported in Fig. 2.

It was also observed that the tests on PERGround nails ended due to the failure of the pipes while standard GFRP pipes were pulled out without damage. In fact, the maximum load of approximately 890 kN (Figure 2) is comparable with the unconfined tensile strength of the pipe, as tested in laboratory (average tensile load equal to 687 kN for corrugated pipes with longitudinal glass fibres content of 68% by weight, as described in Section 4.1).

The observed characteristic of homogeneity of the reinforcement and uniform adherence recurred in all the tested fields since the external sheath limits the influence of the ground conditions (water content, soil density, presence of large voids), of the characteristics of the grout and of the quality of injection on the final nail.

A documented case history on the use of innovative soil nails is reported by Sterpi et al. [11], concerning a tunnel in Southern Italy in highly weathered soft rock mass and in presence of high pore water pressures. The maximum overburden is 65 m and the tunnel section ranges between 150 and 170 m^2. In the most severe conditions, the tunnel face was effectively supported by an average of 50 sub-horizontal nails, 20 m long and overlapped for 10 m along the tunnel axis. In addition, 4 nails enhanced with a coaxial drain were used for coupled reinforcement and drainage actions.

3. The soil nailing at the design stage

The key parameters assessed in the previous section, i.e. the tensile strength and the bond shear strength at the pipe-soil interface, are used at the design stage in both numerical and analytical approaches. In the first case, for instance with the Finite Elements Method, when in the discretisation of the domain into elements a distinction is made between ground mass, nails and interface layer, these properties are used as mechanical parameters of those elements representing the nails (tensile strength) and the interface layer (bond shear strength).

Moreover, when the concept of "equivalent material" is assumed to simulate the presence of soil nailing in a homogeneous equivalent ground mass, the bond properties are used first to convert the mechanical action of the soil nailing in a confinement pressure exerted at the excavation face, and then to convert this confinement in an improvement of the mechanical properties (i.e. the cohesion) of the ground mass ahead of the excavation [3,12,13].

Although the numerical modeling represents the most complete tool for this kind of analyses, characterized by a complex three-dimensional geometry, it involves time and costs that might represent an obstacle at the stage of the preliminary design of the reinforcement system. Therefore, as far as the deformation field is not of prime concern but the tunnel stability only, the preliminary design is often performed with analytical approaches based on simplifying assumptions, that allow for a preliminary calculation, simple yet accurate [14,15,16]. The analytical solutions appear to be in agreement with the more refined numerical predictions and with the experimental observations, in terms of both collapse mechanism and internal pressures that stabilize the excavation. In this kind of approach the medium is generally assumed as homogeneous and the confining effect provided by the soil nailing is converted into an equivalent pressure on the tunnel face. Again, this conversion requires the knowledge of the bond properties and of the maximum tensile strength of the nails.

4. The Glass Fibre Reinforced Polymer pipe characterization

The laboratory characterization of GFRP pipes is necessary, firstly, to investigate the properties of the nails and their interaction with the injection mixture, and to highlight the possible better performance of one nail type with respect to others, under prescribed testing conditions, which can be suitably devised to investigate the influence of various factors on the nail performance. Secondly, the laboratory testing under ideal, controlled and repeatable conditions allows for an accurate and reliable identification of the mechanical parameters of interest that will be taken into account at the tunnel design stage, representing the nails (tensile strength) and the interface layer (bond shear strength), as pointed out in the previous Sections.

4.1 Tensile strength

Before the execution of tensile tests it was necessary to determine the equivalent cross sectional area of Glass Fibre Reinforced Polymer pipe using the same testing procedure prescribed for the Fibre Reinforced Polymer matrix composite bars [17]. The tests consist of immersing the specimen bars (approximately 200mm long) in a graduated cylinder filled with water, and then, once the bars are fully immersed, measuring the volume increase of the liquid. The cylinder must be high enough to prevent overflow once the specimen is immersed. In order to determine the equivalent cross sectional area of the tested specimen, A_p, its average length, l_p, shall be determined. Once the average length of the single specimen has been calculated, its equivalent cross sectional area can be evaluated using the following expression:

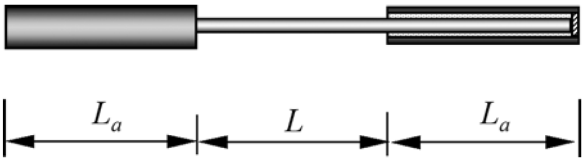
$$A_p = \frac{V_1 - V_0}{l_p},$$

where V_0 e V_1 are the volumes of water in the cylinder before and after immersing the pipe, respectively. Once all the equivalent cross sectional areas of the specimens have been determined, the average value of these quantities which characterise the geometry of the pipe, may be evaluated. Table 1 lists the values determined with these tests.

The tensile test method in ASTM–D–7205 Standard [17] usually is applied to determine the quasi-static longitudinal tensile strength and the elongation properties of fibre reinforced polymer matrix (FRP) composite bars, commonly used as tensile elements in reinforced, prestressed, or post tensioned concrete, but it is easily adapted also to the pipes case. The method requires to equip the specimen by an anchoring system constituted by a steel pipe (Fig. 3) characterized by a wall thickness of 4.8mm or greater. The standard recommends also a minimum grout space of 4mm between the outer surface of the bar and the inner wall of the steel tube. The anchor length L_a is the length required to bond the pipe to the steel tube.

Table 1 *Equivalent cross sectional area values*

Specimen	L_1 [mm]	L_2 [mm]	L_3 [mm]	Average Value [mm]	V_0 [dm^3]	V_1 [dm^3]	A_p [mm^2]
60/40-CRG-1	198,8	200,4	201,5	200,2	650	927	1383,3
60/40-CRG-2	201,3	201,4	200,7	201,1	650	929	1387,2
60/40-CRG-3	206,3	204,6	204,8	205,2	650	928	1354,6
60/40-CRG-4	203,4	206,5	207,6	205,9	650	930	1360,2
60/40-CRG-5	206,2	207,1	207,4	206,9	650	928	1343,8
						Average Value	**1365,8**



FRP bar type	Diameter of the FRP bar, d	Outside diameter of the steel tube	Minimal length of the steel tube, L_a
GFRP	6.4 mm [0.25 in.]	35 mm [1.38 in.]	300 mm [12 in.]
GFRP	9.5 mm [0.38 in.]	35 mm [1.38 in.]	300 mm [12 in.]
GFRP	13 mm [0.50 in.]	42 mm [1.63 in.]	380 mm [15 in.]
GFRP	16 mm [0.63 in.]	42 mm [1.63 in.]	380 mm [15 in.]
GFRP	19 mm [0.75 in.]	48 mm [1.88 in.]	460 mm [18 in.]
GFRP	22 mm [0.88 in.]	48 mm [1.88 in.]	460 mm [18 in.]
GFRP	25 mm [1.00 in.]	48 mm [1.88 in.]	460 mm [18 in.]
GFRP	29 mm [1.13 in.]	48 mm [1.88 in.]	460 mm [18 in.]
GFRP	32 mm [1.25 in.]	75 mm [2.95 in.]	800 mm [32 in.]
CFRP	9.5 mm [0.38 in.]	35 mm [1.38 in.]	460 mm [18 in.]

Fig. 3 *Recommended dimensions of test specimens and steel tubes (ASTM–D–7205)*

Fig. 4 *Tensile test equipment and set-up*

The tests were carried out on a total of 5 samples. To prevent breakage during the test execution, the hollow section of the pipes was previously filled with the same resin used also for the pipe filling. The grip zones of each specimen have been equipped with a steel tube of 1,00m length. The pipe free length was 1,00m. A hydraulic axial loading equipment Amsler, with maximum load of 3000kN, was used under a controlled displacement rate of 2mm/min (Fig. 4). Table 2 collects the test results in term of breaking load and tensile strength evaluated on the basis of the equivalent cross sectional area previously obtained (in Table 1). Figure 5 shows the specimen after failure.

4.2 Pull-out test

Focusing now on the assessment of the interface shear strength, the laboratory investigation is customarily carried out by applying a pull out load, by way of a hydraulic jack, to a pipe driven into a soil model, reconstituted under prescribed conditions, or grouted in a formwork with prescribed grout mixture. Usually, these tests are carried out with the following objectives:

- to assess the response of the reinforcing elements to a tensile load;
- to verify the achievement of a sliding condition, represented by a cumulative residual displacement at the attainment of the maximum pull out load;
- to identify the parameters for the calculation of the interface bond properties, according to a reference standard.

Among the standards, testing procedures have been defined for pull out of generic anchors in masonry and in rock (e.g. [18]), while for Fibre Reinforced Polymer composite bars the standards basically refer to masonry and concrete (e.g. [19]). The simplicity and effectiveness of this method suggested to design a test set-up for standardization of this type of tests when carried out on Glass FRP pipes. In fact, referring for instance to ACI 440.3R-12 standard [19], it was necessary to change the testing set up to fit: (a) the case of a composite pipe made of glass fibres and (b) the application to underground reinforcement. The necessary changes are related to the size of the mortar block in which the pipe is embedded and the clamping method, due to the particular mechanical properties of fibreglass.

Table 2 *Tensile test results*

Specimen	Breaking Load		Cross Sectional Area	Tensile Strength
	[kN]	[ton]	[mm^2]	[N/mm^2]
60/40-CRG-1	944,850	96,31	1365,8	692
60/40-CRG-2	932,253	95,03		683
60/40-CRG-3	939,885	95,81		688
60/40-CRG-4	927,684	94,57		679
60/40-CRG-5	943,885	96,22		691

Fig. 5 *Glass Fibre Reinforced Polymer pipes subjected to tensile tests after failure*

The tested GFRP nails are CRG corrugated pipes, having a circular hollow section of outer diameter $Ø_{out}$ = 60 mm and internal diameter $Ø_{int}$ = 40 mm, and a total length L = 750 mm. To prevent breakage during the test execution, the hollow section of the pipes was previously filled with resin. Then, each pipe was grouted with cement mortar within a metal formwork, having 300 mm in internal diameter, 410 mm in height, and 0.8 mm in thickness. The embedment length inside the cement mortar block is ℓ = 300 mm (Figure 6).

The large ratio between the diameter of the grout block and the outer diameter of the pipe (in this case equal to 5), together with the reduced wall thickness of the formwork (0.8 mm), allow to limit the mechanical contribution of the formwork itself to the pull out resistance, i.e. its possible confinement action. At the same time, the ratio between the embedment length and the outer diameter of the GFRP anchor ($\ell/Ø_{out}=5$) allows to approximate the adherence between the pipe and the cement mortar as a uniformly distributed effect.

The results are shown with reference to 6 specimens, three of them tested 24 hours after casting and the other three 48 hours after casting, using the electromechanical testing machine Schenck (maximum load equal to 1000 kN), able to apply tensile and compression loads. For the correct positioning of the sample a suitable framework was designed (Figure 6). The loading frame is constituted by four steel columns, acting as supports and vertically driving the transversal plate: this optimizes the stiffness of the frame in the loading direction.

The grout mixture was prepared with a water/cement ratio equal to 0.45 (in particular: 25 kg of cement, 11.25 l of water, 0.2 kg of high plasticizer). The density of mixture was found to be equal to 1883 kg/m^3. Its strength characteristics, assessed by simple compression tests on cubic specimens of 100 mm side, resulted in mean values of compression strength equal to 6.6 N/mm² and 22.4 N/mm², respectively 24 and 48 hours after casting.

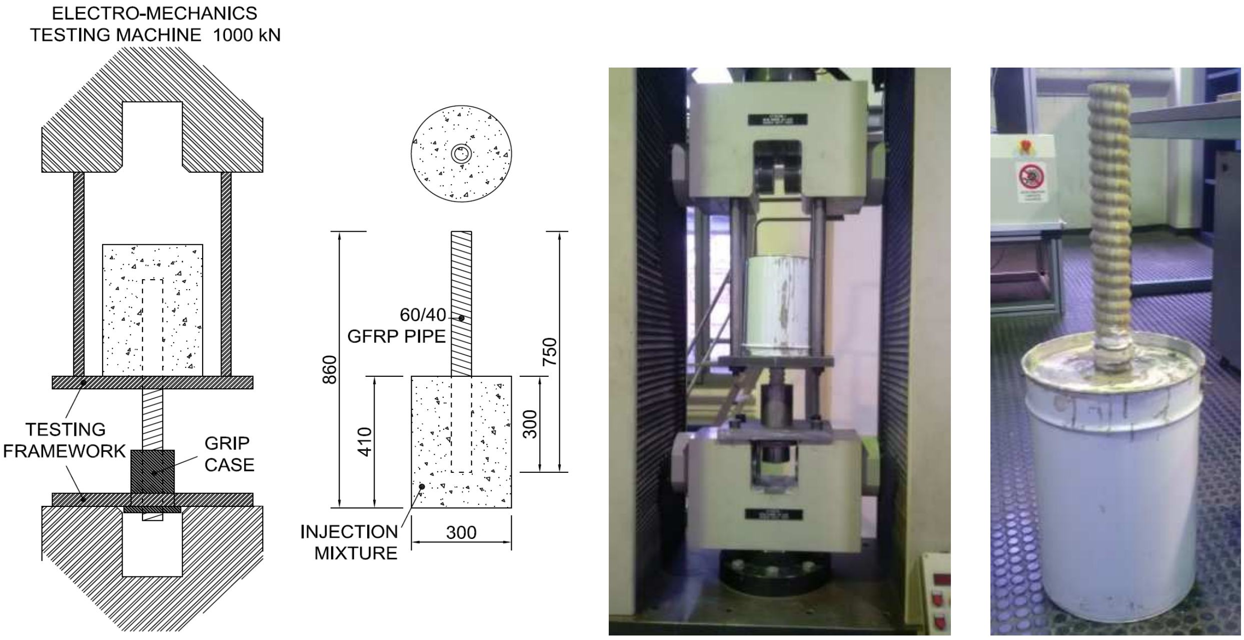
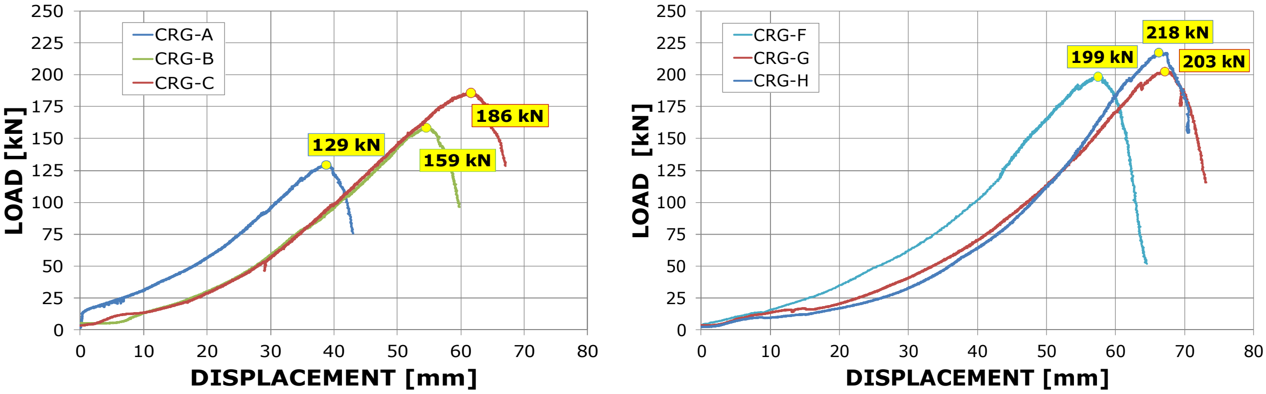


Fig. 6 *Sketch and pictures of the pull out test equipment and set up*

The pull out tests were carried out first by inserting the free head of the GFRP pipe in a protective steel cylinder case for a correct gripping and subsequent application of the tensile load. This was necessary in order to extend the gripping surface, thus reducing the risk to damage the GFRP element. The pull out phase was performed under displacement control, with an applied displacement rate of 0.02 mm/s, with continuous load and displacement monitoring, till the complete pull out. The results (Figure 7) show that the CRG corrugated pipes offer a high pull out resistance that slightly increases with time, from 24 to 48 hours, as a consequence of the mortar hardening. The maximum tangential stress at failure τ_{max} , defined as the bond strength and reported in Table 3, can be calculated according to the equation:

$$\tau_{max} = \frac{F_{pull-out}}{C_b \ell}$$

where: $F_{pull\text{-}out}$ is the pull-out load at failure; C_b is π times the pipe diameter; ℓ is the embedment length of the sample within the cement grout block. Considering the diameter of the tested pipes (60mm) and the embedment length (300mm), the bond strength is then evaluated assuming the maximum value of load.



(a) (b)

Fig. 7 *Laboratory pull out tests on CRG corrugated pipes after (a) 24 hours and (b) 48 hours*

Table 3 *Pull-out load and bond strength*

Sample	Time	Load	τ_{max} – bond strength	
	[h]	[kN]	[kN/m^2]	[N/mm^2]
CRG-A	24	129	2290	2,290
CRG-B	24	159	2810	2,810
CRG-C	24	186	3295	3,295
CRG-F	48	199	3527	3,527
CRG-G	48	203	3590	3,590
CRG-H	48	218	3857	3857

As to the pull out performance of CRG pipes compared with standard ones, it can be pointed out that in previous tests the standard AM pipes led to pull out loads equal to about 50-55% of the values reached by CRG pipes, under the same testing conditions [9]. The laboratory tests therefore confirm the better performance of CRG pipes already highlighted in field tests (Figure 2), likely due to the different mechanical interaction between the pipe and the grout (Figure 8). In fact, while in the case of standard pipe the fractured zone observed in the sample after the test is localized around the pipe surface and the grout block appears unaffected, with the pipe characterized by a corrugated profile the fractures extend within the grout, proving the activation of compression stresses in the grout that lead to high pull out loads.

Fig. 8 *Observed different interaction between pipe and grout in pull out tests of standard (left) and corrugated (right) GFRP pipes*

5. Conclusions

An accurate laboratory characterization of the properties of soil nails has become a necessary step in the process of the design of underground stabilization works. These properties have been identified as the tensile strength of the unconfined pipe and the interface shear strength, or bond adherence, between the pipe and the surrounding ground. In the case of Glass Fibre Reinforced Polymer pipes the standards commonly used as reference are those originally defined for different fibre reinforced composite bars and for different applications, and therefore specific provisions need to be introduced for adapting those standards to the case of GFRP pipes.

As to the tensile strength tests the specific provisions to be introduced concern the clamping of the specimen, i.e. the length of the clamping zone and the filling of the hollow pipe, within the same zone, with a suitable resin or grout. This helps to avoid localized damages of the pipe, that can be either the whole breakage of the pipe or the simple cutting of the glass fibres.

For the pull out tests the same provision of hollow pipe filling in the clamping zone is suggested and, in addition, it is recommended to use formworks of reduced thickness and of large diameter, with respect to the outer diameter of the pipe to be tested. This recommendation is meant to avoid, or limit, the influence of the formwork stiffness on the pull out response and to help developing an interaction, between the pipe and the surrounding mass, more representative of what is to be expected in real site conditions. This effect is well highlighted by comparing the failure modes of standard and corrugated pipes, the latter involving the grout mass for an extension not limited to the pipe–grout interface.

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