GFRP L'utilisation du TBM GFRP using in TBM Tunneling

Abstract

Le développement et la recherche de nouveaux matériaux ont conduit, au cours des dernières décennies, à une plus large utilisation des matériaux composites renforcés en fibres dans le monde de la construction civile, y compris les matériaux en fibres de verre (GFRP). Les propriétés de ces matériaux ne soient pas sensibles aux phénomènes de corrosion, de ne pas être conducteur et d'être plus faciles à détruire par rapport à l'utilisation des éléments en acier, on privilégie l'emploi dans certains contexts spécifiques, et en particuliers, dans le cadre des travaux souterrains, jusque-là on peut présenter des environnements très agressifs ou soumis à des courants de fuites. Le présent article désigne l'utilisation des éléments en GFRP dans le domaine de la réalisation de tunnels creusés par TBM et en particulier, pour la mise en oeuvre des revêtements des segments préfabriqués. Dans ce contexte, l'utilisation des barres et des réseaux en GFRP peuvent remplacer complètement la traditionnelle armature en acier ou constituer des éléments de renforcement à superposer sur l'armature métallique. L'utilisation des segments préfabriqués entièrement armés avec des barres en fibre de verre peuvent être utile dans les environnements très agressifs, comme les tunnels marins, ou comme les éléments de discontinuité électrique dans les tunnels ferroviaires, d'où une bague entière de revêtement en GFRP représente une efficace " joint diélectrique " vers les courants de fuites. Bien au contraire, l'utilisation des treillis en GFRP est extrêmement utile dans la protection des bords des segments, en considérant la possibilité de réduire les valeurs de couverture de béton généralement prévues pour les armatures métalliques. Enfin, l'adoption des renforcements en fibre de verre est avantageuse lorsque à prévoir la démolition partielle des structures de revêtement, par exemple, en correspondance à la construction de niches et de by-pass, ou pour la réalisation de travaux temporaires, tels que les prédispositions du chantier pour le lancement de la TBM successivement enlevée ou des ouvrages de soutènement afin du début des excavations. L'article présente en détail les différents cas d'application, en clarifiant les points forts. En outre, après avoir décrit les spécifications techniques des matériaux utilisés, cet article illustrera les procédures de conception et les méthodes de calcul appliquées, ainsi que des preuves provenant d'essais expérimentaux.

Abstract

The development and research into new materials led, over recent decades, to a widespread use of composite fiber-reinforced materials in the world of civil construction, including fiberglass materials (GFRP). The properties of these materials cannot be subjected to corrosion, not being conductive, and easily to demolish in spite of the use of steel elements, favoured their use in specific context particularly in underground works, where aggressive environments or stray currents should prevail. This article explains the use of GFRP elements in the field of tunnels construction with TBM tunneling and in particular, the execution of lining with precast segments. In this context, the use of bars and GFRP nets could replace totally the traditional steel reinforcement or constitute strengthening components to overlap steel armature. The use of precast reinforced segments with fiberglass bars could be useful in highly aggressive environments, such as in marine tunnels, or as electric discontinuity elements in railway tunnels, where the entire GFRP lining ring represents an efficient "dielectric joint" towards stray currents. Instead, the use of GFRP nets is quite appropriate in protecting the edges of the segments, considering the possibility of reducing the values of concrete cover usually provided for metal reinforcements. Finally, the implementation of fiberglass reinforcement is favorable in circumstances where partial demolition of lining structures are provided, for example, in achievement of niches and by-pass, or in accomplishment of temporary works, such as launching ramp for TBM throw consequently removed or metal frameworks aimed at the startup of the excavation. This article will detail the various practical instances clarifying the strengths. In addition, after describing the technical specifications of the materials used, the article illustrates the project practices and the calculation methodologies applied, as well as the evidences deriving from experimental tests.

GFRP L'utilisation du TBM

GFRP using in TBM Tunneling

Aniello A. GIAMUNDO, *ATP S.r.I., Angri, Italy* Giuseppe VAGO, *ATP S.r.I., Angri, Italy* Martino GATTI, *Rocksoil S.p.A, Milan, Italy* Giuseppe LUNARDI, *Rocksoil S.p.A, Milan, Italy*

1 Introduction

The development and research into new materials led, over recent decades, to a widespread use of composite fiber-reinforced materials in the world of civil construction, including fiberglass materials (GFRP). The properties of these materials - cannot be subjected to corrosion, not being conductive, and easily to demolish in spite of the use of steel elements - favoured their use particularly in underground works, where aggressive environments or stray currents should prevail. This paper explains the use of GFRP elements in the field of tunnels construction with TBM tunnelling. In this context, the use of GFRP bars and nets could replace totally the conventional steel reinforcement or constitute strengthening components to overlap steel armature.

The availability of new Codes and Standards (ACI440, CNR DT203) gives the Designers and Stakeholders detailed guidelines for the design and construction of structural concrete reinforced with FRP bars, so the use of these materials are today of common practise. Experimental programs, by full scale tests and monitoring tests, i.e. Meda et al. (2014), have been performed in order to check structural behaviour in Serviceability and Ultimate Loads Conditions. All these data and information support technical applications, especially in environmental conditions where the steel reinforcement is not suitable. In these special context the higher cost of fibreglass material can be easily balanced considering the overall costs related to the maintenance during the construction life period.

This paper presents the up-today situation about the use of GFRP elements in TBM tunnelling, highlighting the application in which the use of fibreglass bars and nets could be very useful and advantageous, in spite of their costs. GFR properties and technical specifications will be described in detail in order to focus the most interesting applications. A brief summary of design rules, for dimensioning and static verifications will be illustrated too. Finally some experimental data will be presented.

2 GFR Properties and technical datasheet

The behaviour of GFRP bars are depending on their physical and mechanical properties, which are very important to point out the advantages of the use of these materials on respect to common steel reinforcement. The techniques used to manufacture these products, such as pultrusion, braiding and weaving, and factors such as fiber volume, type of fiber and resin, fiber orientation ... play an important rule in defining FRP characteristics. Anyway several Standards developed test methods to define in detail the material characteristics, i.e. in Appendix B of CNR-DT 203/2006 and ACI-440-3R-04.

For TBM tunnelling applications, two kinds of materials are generally used depending if the structural element is provisional, for construction period, or permanent for longtime service: for provisional elements, GFRP bar are made by polyester resins, for permanent structures vinylester resins are involved. GFRP density is ranging between 1.80 g/cm³ up to 2.10 g/cm³, approximately one-fourth that of steel; reduced weight lowers transportation costs and may easy handling of the bars, especially of segment reinforcement cages or diaphragm walls cages. The coefficient of thermal expansion varies in the longitudinal and transversal directions; the longitudinal is dominated by the properties of the fibers (4.5- 5.5×10^{-6} °C, comparison to concrete's coefficient equal to $4-6 \times 10^{-6}$ °C), while the transverse coefficient by the resin (21.0-23.0×10⁻⁶°C).

From a mechanical point of view, it could be noticed that GFRP bars do not exhibit any plastic behaviour (yielding) before rupture; the tensile behaviour is characterised by a linear elastic stress-strain relationship. The tensile strength generally varies with the diameter of bars, into the range 500-1200 MPa, showing a reduction of strength according to an increase of the diameter: for example > 690 MPa for bars with diameter 18 mm, > 850 MPa for diameter equal to 8 mm (with an increase of about 25%). The rupture deformation is in the range 1.2-3.0%. The elastic modulus is ranging between 35 up to 50 GPa, generally > 40 MPa. The strength and the elastic modulus in compression are lower on respect to tensile condition, up to 50%.

Properties	GFRP Rebar	Steel Rebars
Tensile strenght (MPa)	700 ÷ 1200	350 ÷ 550
Elastic modulus (GPa) *	35 ÷ 50	210
Elongation (%)	1,5 ÷ 3.0	15 ÷ 30
Density (g/cm ³)	1,8 ÷ 2,1	7,8
Thermal conductivity (W/m°C)	0,25 ÷ 0,35	100 ÷ 250
Dielectric Strength (KV/m)	5 ÷ 15	
Resistivity (Ωcm)	10000	9,68 × 10−11
Longitudinal thermal expansion coefficient $\lambda \ ^{\circ}C^{^{-1}}$	$0,5 \times 10^{-5}$	$1,2 \times 10^{-5}$
Transversal thermal expansion coefficient $\lambda\ ^\circ C^{-1}$	$2,1 \times 10^{-5}$	1,2 × 10 ⁻⁵

Table 1. GFRC technical characteris	stics
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* Strength and Elastic Modulus in compression are lower on respect to tensile condition, up to 50%.

Time-dependent behaviour is related to creep phenomena and fatigue; various studies have shown that GFRP concrete structures show better behavior referring to fatigue resistance under cyclic loads than similar structures reinforced with steel (Carvelli et al., 2010, El Ragaby et al., 2006 Karthick et al., 2014). ACI-440 highlights that bond behaviour has not been sufficiently investigated for fatigue approach, so conservative design criteria are recommended. The most interesting aspects is that GFRP cannot be subjected to corrosion and aren't conductive elements; resistivity is very high on respect to steel. The main GFRP properties are reported in Table 1.



Figure 1. GFRP reinforcement for segment linings

One of the most critical aspects of the durability of reinforced concrete structures is caused by corrosion of steel reinforcement. Steel in the concrete is protected by corrosion as long in concrete there is an alkalinity between PH12 and PH14. This happens with fresh concrete, and under these conditions, a thin passivating film (formed by oxides with a thickness of a few molecular layers) is created that prevents corrosion of the reinforcement. However, over time, the alkalinity of the concrete is neutralized by carbon dioxide coming from outside and thus begins the concrete carbonation phenomenon. This phenomenon is not harmful to the concrete itself, rather increases its compression characteristics, but causes a decrease in alkalinity that soon reaches values between PH9 and PH11. Under PH11.5 the passive protective film is dissolved and thus the corrosion of the steel reinforcement begins. If you are also in the presence of chlorides, present in de-icing salts or in coast structures, everything gets worse. GFRP reinforcements, made up of vinylester resin and "E" glass, have a completely different behavior, "suffer" more in alkaline environment while they are completely inert in acidic or neutral environments. Paradoxically, the more carbonation of the concrete increases the durability of the GFRP reinforcement.

In the event of fire, the fibrous component of the bars in GFRP resists temperatures greater than 1000 °C while the polymer matrix degrades at temperatures above 150-200 °C. This would suggest that,

due to the loss of adhesion to the concrete, GFRP bars can't be used without adequate fire protection. In reality it is proven by laboratory tests that using closed stirrups, the glass fiber component retains its characteristics and allows to pass the R120 certification tests, even in the absence of protections and with reduced concrete cover; fire tests have been developed i.e. by the Russian Research – Institute of Fire Protection for "IC PROZASK" Limited (2016).

3 Application in TBM Tunnelling

The use of GFRP is very interesting in TBM tunnelling owing to the several application which interest both the construction stage both the long term life of the tunnels. The Authors have already applied this technology as reinforcement for concrete in several contexts, taking into account the potentiality of the GFRP products. In detail the following applications could be considered:

- precast reinforced segments with fiberglass bars could be used in highly aggressive environments, such as in marine tunnels, where the use of steel reinforcement is strongly disapproved due to the high risk of steel corrosion, with spalling of concrete cover and degradation of concrete. This solution could be very interesting when marine sand is used for aggregate in preparing concrete;
- <u>special precast segments</u> could be used as a part of the final lining, in case of partial demolition of the lining structures, for example in achievement of niches, lay-by and by-pass. In this situations it is preferable to adopt GFRP reinforcement, easier to demolish with respect to steel reinforcement, especially if some openings should be made inside the segment geometry;
- <u>the use of GFRP nets</u> is quite appropriate in protecting the edges of the segments, considering the possibility of reducing the values of concrete cover usually provided for metal reinforcements; this system is very useful to minimise the rupture which usually happen during TBM advance owing to handling and erection phases, mainly in the tunnel starting period (learning curve). Owing to a special production system, it is possible to prepare a GFRP corner net, with defined geometry;
- <u>special rings</u>, reinforced by GFRP bar, could be placed along the tunnel alignment, each 300-500 m, with function of "dielectric joint" towards stray currents. This function is typical of railways or subway tunnels, where the risk of stray current is very high. An entire GFRP lining ring represents an efficient electric discontinuity element, able to stop current migration;
- <u>GFRP handrail</u>, compliant with the requirements of the European prescriptions of STI-RTI-2014 Safety in Railway Tunnels due to hanks, to the complete electrical insulation and the non-toxicity and transmittance of fumes in case of fire.

In all these cases, GFRP elements work for the entire service life of the tunnels; durability concepts have to be implemented, about kind and quantities of fibers and resins and referring to design static criteria. Figure 1 illustrates the use of GFRP bars for the reinforcement of segment linings. The geometry of the GFRP cage is quite similar to a steel one, with longitudinal and transverse bars, plus stirrups to connect the internal and external reinforcement layers.



Figure 2. GFRP "closed" stirrups

Special stirrups are placed in the pushing side, where local tensile stress are connected to the application of the TBM thrust by pushing jacks. Bars with diameters ranging between 10 mm and 20 mm are usually adopted, very similar to the steel ones, with stirrups' diameter into the range 8-12 mm. It's very interesting to notice that special GFRP "closed" stirrups are available by the fibreglass market, as showed in Figure 2, very performing in confining the main bars primarily subjected to the external ground and groundwater pressures. These "closed" stirrups are also very efficient in controlling the stress distribution in concrete, connected to the pushing loads.



Figure 3. GFRP corner net

Figure 3 shows the GFRP corner net, to use in manufacturing steel reinforced concrete segment, to protect the corner. Special 3D geometry are usually employed, in order to cover the whole corner of the segment, for each of the four sides. The use of nets with diameter of 5 mm and mesh of 100×100 mm is suggested. The production of this corner net is made by impregnating a single continuous beam glass fibres with vinylester resin, to ensure a complete reinforcement anchorage in concrete. This allows to completely transfer the stress from the concrete to the reinforcement, even with small concrete covers. A trial test is in program involving about 250 annular ring (9 segments, thickness 0.55 m length 2.20 m), in order to evaluate the statistic reduction of damage connected to the use of corner nets.

Some interesting applications are referred to provisional works, during the TBM break-in and breakout. Two main cases are here illustrated:

- the so called "soft eyes", i.e. the use of GFRP reinforcement for the diaphragms interested by TBM excavation. For the excavation of underground stations and shafts, retaining walls are generally used, such as diaphragms or piles supported by anchors or steel frame and concrete slabs. When the tunnels alignment crosses the station, part of these retaining walls have to be demolished by the TBM during the break-in and break-out operations. It's known that the TBM's cutter head cannot manage with steel elements, which could generate TBM consumption or ruptures. For this reason is very convenient to reinforce the retaining walls interested by TBM excavation by GFRP bars, able to be demolished without problems for TBM safety; this application is nowadays very frequent and represent a common practice;
- <u>sometimes the launching ramps and cradles for TBM starting</u> present provisional geometries which are in conflict with future part of the permanent structures, such as tunnel portals or buildings for equipments and managing systems. In this cases part of the ramps and cradles can be constructed employing GFRP bars, so to make easy its future demolishing.

Figure 4 shows a typical "soft eye" with GFRP bars; the European Standard BS-EN-1538-2000 specifies the execution of diaphragm walls and the practical aspects which must be taken into account in the production of design documents; at chapter 7.4 gives rules for reinforcement cages, about vertical and horizontal reinforcements (number of bars for each meter, minimum diameter and spacing), concrete cover and tolerances.

Figure 5 represents the use of GFRP bars for the construction of a part of a cradle for launching the TBM for the excavation of "Santa Lucia" Tunnel, located in the Highway A1 Bologna-Florence, near Barberino di Mugello, by the Contractor Pavimental. Considering the large diameter of the TBM, about 16 m, very important cradles have been casted in situ; part of this launching structures will be adopted for service structure too, as part of the portal's foundation and as the basement of the technical operation rooms. Part should be demolished, being it is interfering with the final outlet of the portal.

The portion to be demolished has been designed employing, as reinforcement for concrete structure, GFRP rebar so to make easier the future demolition. With reference to the Figure 5, representing schematic sections of the launching cradle, the grey part represents the steel reinforced structure (mainly basements and foundations), while the blue part represents the provisional structures, reinforced by GFRP rebar, aimed at the construction phase of tunnel.



Figure 4. GFRP "soft eye"

Once completed the tunnel excavation, these blue parts will be demolished, and the final structures - represented in red - will be casted, using steel reinforced concrete. Special GFRP rebars connect the two structures, grey (permanent) and blue (provisional), guaranteeing the monolithic behavior of the structural system. Special pre-assembling of the GFRP cages have been employed to make easy and fast the construction operations. The statical verification of the structures has been performed by FEM Analyses, as reported in Figure 6, according to the procedure illustrated in the following chapter 4.



Figure 5. GFRP TBM cradle

4 Reference Codes and Design Criteria

ACI 440.1R-06 (2006) is a first reference code for designing GFRP reinforcements. The Authors have been involved in the preparation of the document CNR-DT 203/2006 (2006), where precious suggestions for the dimensioning of GFRP elements are reported. Ultimate and Service Limit State (ULS and SLS) have to be considered for static calculation of GFRP reinforced elements; the following hypothesis should be considered: plain deformation for structural section, no slip between concrete and GFRP bars, no tensile strength for concrete and no compressive strength for fiberglass bars, stress-strain relationship for concrete according to EC2 or "stress-block" (1992) and stress-strain relationship for fiberglass elastic and linear up to rupture. Applying the "partial coefficient" method, the following equation should be checked for each limit state:

$E_d \le R_d$

(1)

where E_d represents the design value of acting forces or effect and R_d is the design value of strength for the considered limit state. The design actions are defined according to usual Codes. The design value for material's strength is defined according to the following relationship:

Where X_k is the characteristic value, γ_m is the partial coefficient and η is the conversion factor which takes into account the environmental and long-term aspects. γ_m for fiberglass elements is equal to 1.5 for ULS and 1.0 for SLS. The factor η is the product of η_a (environmental) and η_l (long-term: fatigue, creep); where no experimental data are available the suggested factors are: η_a is 0.8 for concrete in dry conditions and 0.7 for concrete in wet conditions; for provisional works η_a is equal to 1.0. η_l is 0.30 for SLS and 1.0 for ULS; it could be noticed a strong reduction of GFRP strength for long-term condition in SLS, this condition has to be deeply investigated by tests program. In the following chapters assumptions for calculations are reported.



Figure 6. GFRP TBM cradle – FEM Analyses

4.1 Flexure

According to the fundamental hypothesis above reported, the bending rupture occurs, as showed in Figure 7a, when the ultimate plastic strain in compressed concrete (ε_{cu}) is reached – zone 2 - or, with reference to GFRP, when the FRP bars reach – zone 1 - the ultimate stress ε_{fd} , defined by the following formula:

$$\varepsilon_{\rm fd} = 0.9 \cdot \eta_{\rm a} \cdot \frac{\varepsilon_{\rm fk}}{\gamma_{\rm f}} \tag{3}$$

where η_a and γ_m are above discussed and ε_{tk} is the characteristic tensile strain, ranging between 1.5-3.0% (defined by laboratory tests, i.e. for rebars of 18 mm is equal to 0.0173). Considering the condition of linear strain for RC section and the position of the neutral axis derived by the equilibrium equation N = 0 in the axial direction, the nominal flexural strength M_{rd} can be derived by the bending equilibrium equation; Figure 7b reports a typical ULS domain for GFRP segment. The minimum tensile reinforcement area must guarantee the nominal flexural strength M_{rd} is greater than 1.5 the flexural strength at first cracking M_{cr}. If the GFRP elements haven't shear reinforcement, the tensile GFRP area must be > 0.01 bd (with b and d the base and the effective height of the RC section).



Figure 7. a) Bending rupture for GRFP r.c. b) ULS domain

For SLS it's necessary to check: 1) the stress values, 2) the deformation behavior and 3) the cracks' conditions. The elastic behavior is valid, so there is proportionality between the stresses in concrete and in FRP according to the elastic modulus ratio $n_f = E_{FRP}/E_c$, both for stage I uncracked and stage II fully cracked. For quasi-permanent condition stresses in FRP elements should be $\sigma_{FRP} \leq f_{td}$ with f_{td} evaluated by (2) using the SLS coefficient. The deformation for GFRP concrete elements can be evaluated integrating the curvature' diagrams taking into account cracking and concrete tension

stiffening (non linear analyses); the limits are the same referred to steel RC. For cracking evaluation, experimental data showed that formula used for steel RC are valid for FRP RC too, in term of cracks spacing and tension stiffening effect; this isn't valid for smooth rebars. The cracks' opening limit is 0.5 mm, greater on respect to steel RC limits (generally 0.1-0.3 mm).

4.2 Shear

Shear statical check must be done just for USL. It is allowed the construction of slabs and plates without shear reinforcements, if the structure is able to distribute the loads. Shear resistance for GFRP reinforced sections without specific shear reinforcements can be evaluated as

$$V_{\rm Rd} = \min\left\{V_{\rm Rd,et}, V_{\rm Rd,max}\right\}$$
(4)

where $V_{Rd,max}$ is the concrete compressed rod resistance (to be evaluated according to current Norms) and $V_{Rd,ct}$ is:

$$V_{\rm Rd,ct} = 1.3 \cdot \left(\frac{E_{\rm f}}{E_{\rm s}}\right)^{1/2} \cdot \tau_{\rm Rd} \cdot k \cdot \left(1.2 + 40\rho_{\rm l}\right) \cdot b \cdot d \tag{5}$$

with $E_{f_r}E_s$ = elastic modulus of FRP bars and steel (N/mm²), τ_{Rd} = 0,25 f_{ctd_r} k = (1,6 - d) ≥ 1 (d espressed in m) and $\rho_l = A_{f'}(b \times d) \le 0,02$. If GFRP shear reinforcements are provided, shear resistance can be evaluated as follows, considering the GFRP stirrups contribute $V_{Rd,f}$ (perpendicular stirrups):

$$V_{\rm Rd} = \min\left\{V_{\rm Rd,ct} + V_{\rm Rd,f}, V_{\rm Rd,max}\right\} \qquad V_{\rm Rd,f} = \frac{A_{\rm fw} \cdot f_{\rm fr} \cdot d}{s}$$
(6)

where A_{fw} is the area of stirrups disposed with step *s*, f_{fr} is the reduced design strenght = $f_{fd}/\gamma_{f\phi}$ ($\gamma_{f\phi}$ is a partial factor that reduce the tensile strenght to take into account bending effects. Indicatively $\gamma_{f\phi} = 2$). The minimum shear reinforcement must be greater than 0.06 $f_{ck}^{-1/2}$ bs/0.004 E_f with minimum equal to (0.35bs)/0.004 E_f . Minimum stirrups: 3 for each meter and spacing less than 0.8 of the effective height.

4.3 Details

For beams elements the secondary reinforcements must be greater than 20% of the main reinforcements. The minimum bond length is equal to $l_d=0.1 d_f \times d_b$ with σ_f stress in the rebar and d_b the rebar's diameter (> 400 mm), with radius of bending > 6 diameters. The suggested concrete cover is > 25 mm for plate and 30 mm for beams. For pillar an amount of GFRP area greater than 1.5% of the gross section is request, with stirrups spacing less than 15 diameters (< 250 mm). Special spacing has to be provided for the ends of the pillar.

5 Experimental data

For the applications above described, several tests have been performed in order to check the experimental behavior of GRFP elements to compare with the predictive models and with the performing of the usual Steel RC structures. Precast GRFP segments have been tested with different geometry and thickness (Meda et al. 2014). On September 2014, the 280 mm thickness segment used by "MetroBlu" for the construction of MetroLine 4 in Milan (length about 3500 mm, width 1400 mm) have been tested in bending and for axial loads (to simulate the TBM thrust by jacks); the experimental program considered tests for SRC segments and GFRP segments.



Figure 8. Bending rupture for GRFP and SRC

In Figure 8 the diagrams "Load (KN) - Displacement (mm)" in bending for SRC and GFRC are reported: it could be noticed the first cracking bending (Mcr) for SRC, 140 KN, is greater on respect to the GFR one, equal to 80 KN, due to lower GRF elastic modulus. Otherwise the ultimate bending (M_r) is greater for GFRC segment, 450 KN on respect to the SRC ultimate bending 370 KN, considering the higher tensile strength of fiberglass. The deformation behavior was comparable; the distribution of cracks was quite similar too: the cracks opening were greater for GFRC segment, once again considering the different elastic modulus for fiberglass and steel ($E_{\rm s}$ / $E_{\rm f}$ ~5), but cracks were permanent in SRC segment, where the yielding stress limit of steel was reached, while in GFRC segment cracks closed in the unloading phase owing to the linear elastic behavior of fiberglass. Similar considerations could be done for axial tests too. The tests' results were compliant with the predicted value for ultimate bending and axial loads, according to chapter 4's rules: to a load of 450 KN, applied in the middle of the segment, corresponds a bending moment equal to 228 KNm, which is very similar to the theoretical one. A real test has been also executed, placing one ring with GFRP segments during the construction of the MetroLine 4 at Q.re Forlanini Station, to be tested as a dieletric joint: no problems were recorded and the static performance of the GFRP ring, monitored by strain-gauges in concrete and topographic targets placed on the external surface, was the same of a common SRC segment.

Axial load tests were executed to check the performance of the GFRP net placed in the corner of the segment; the tests, executed at the "Tor Vergata" University's structural lab in Rome applying a corner load on GFRP and SRC concrete cubes, show the presence of fiberglass net reduces the concrete spalling at a very cortical area, unlike in SRC cube, where, owing to higher concrete cover, cracks and spalling interest an huge part of the corner; Figure 9a shows the details of the cubes. Some recent tests, performed by Russian Institute for Fire protection (2016), certified R120 for GFRP segment with 0.8 kg/m³ of polypropylene fibers and 10 kg/m³ of fiberglass fibers, showing strength condition for 125 minutes under constant static loads of 490 KN placed in the middle of the segment.





Figure 9. a) Cube tests with GFRP nets b) Fire test for R120 certificate

b)

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