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The use of GFRP reinforcing elements & the mechanized excavation method

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ABSTRACT

This article explains the use of GFRP elements in the field of tunnels construction with TBM tunnelling and in particular, the execution of lining with precast segments. In this context, the use of GFRP bars and 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 concrete cover usually provided for metal reinforcements. Finally, the implementation of fiberglass reinforcement is favourable in circumstances where partial demolition of lining structures are to be considered, as for instance for construction of niches and by-pass, or in accomplishment of temporary works, such as launching ramp for TBM to be then removed or metal pushing frameworks at the start-up of the excavation. 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 derived from experimental tests.

Key Words: GFRP, reinforcing elements, mechanized excavation method, segment, soft-eye.

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 be demolished in comparison with steel elements - favoured their use particularly in underground works, where aggressive environments or stray currents could prevail.

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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 GFRP bars, so the use of these materials is 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 contexts 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 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, and replace totally the conventional steel reinforcement or constitute strengthening components to overlap steel armature. 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. Some experimental data will be finally presented, specially referred to different reinforcement cage types.

2. GFR PROPERTIES AND TECHNICAL DATASHEET

The behaviour of GFRP bars is 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 fibre volume, type of fibre and resin, fibre orientation … play an important rule in defining GFRP characteristics. Several Standards and Normds 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.

Properties	GFRP Rebar	Steel Rebars
Tensile strength (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 λ $°C^{-1}$	$0,5 \times 10^{-5}$	$1,2 \times 10^{-5}$
Transversal thermal expansion coefficient λ $°C^{-1}$	$2,1 \times 10^{-5}$	$1,2 \times 10^{-5}$

* Strength and Elastic Modulus in compression are lower on respect to tensile condition, up to 50%.

Table 1. GFRP technical characteristics

For TBM tunnelling applications, two kinds of materials are generally used depending if the structural element is provisional, to be effective just for construction period, or permanent that is active for long time 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 fibres (4.5-5.5×10-6°C, in comparison to concrete's coefficient equal to 4-6×10-6°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%.

Time-dependent behaviour is related to creep phenomena and fatigue; various studies have shown that GFRP concrete structures show better behaviour 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 chlorides are present too, for instance 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 behaviour, "suffer" more in alkaline environment while they are completely inert in acidic or neutral environments. Paradoxically, 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 cannot 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 THE MECHANIZED EXCAVATION METHOD

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. In detail, taking into account the potentiality of the GFRP products, the following applications could be considered:

- precast segments reinforced 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;
- special precast segments 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 these 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;
- 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; this system is very useful to minimise the rupture which usually happen during TBM advance in 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;
- special rings, 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;
- GFRP handrail, 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 fibres 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 stresses 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, as further described.

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 rings (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.

Figure 3. GFRP corner net

Some interesting applications are referred to provisional works, during the TBM break-in and break-out. 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 represents a common practice;

- sometimes launching ramps and cradles for TBM starting present provisional geometries which are in conflict with future part of the permanent structures, such as tunnel portals or buildings for equipment and managing systems. In these cases part of the ramps and cradles can be constructed employing GFRP bars, so to make easy their 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 the "Santa Lucia" Tunnel, located in the Italian 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 thiese 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, because of its interfering with the final outlet of the portal. The portion to be demolished has been designed employing, as reinforcement for concrete structure, GFRP rebar 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 behaviour of the structural system. Special pre-assembling of the GFRP cages has been employed to make easy and fast the construction operations. The static 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.

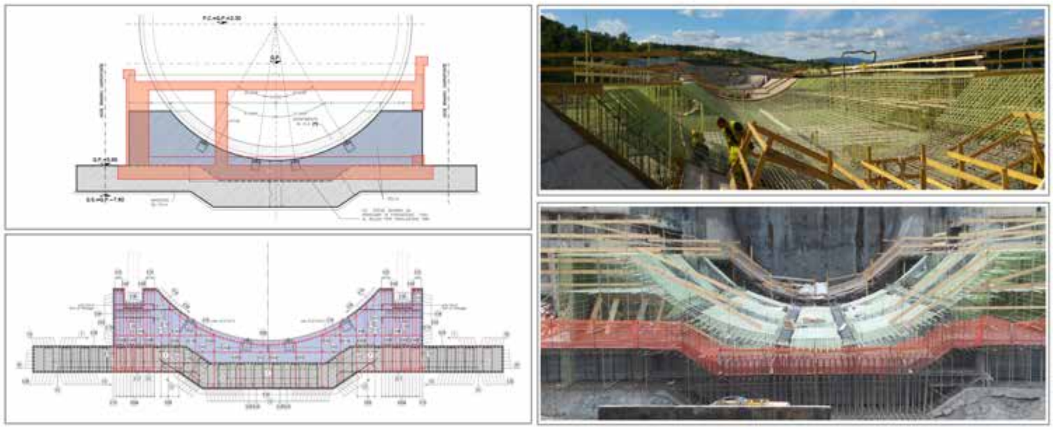

Figure 5. GFRP TBM cradle

4. REFERENCE CODE 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; the following hypotheses 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:

$$E_d \leq R_d \tag{1}$$

where Ed represents the design value of acting forces or effect and Rd 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 Xk is the characteristic value, γm is the partial coefficient and η is the conversion factor which takes into account the environmental and long-term

$$X_d = \eta \, X_k / \gamma_m \tag{2}$$

aspects. γm for fiberglass elements is equal to 1.5 for ULS and 1.0 for SLS. The factor η is the product of ηa (environmental) and ηl (long-term: fatigue, creep); where no experimental data are available the suggested factors are: ηa is 0.8 for concrete in dry conditions and 0.7 for concrete in wet conditions; for provisional works ηa is equal to 1.0. ηl 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.

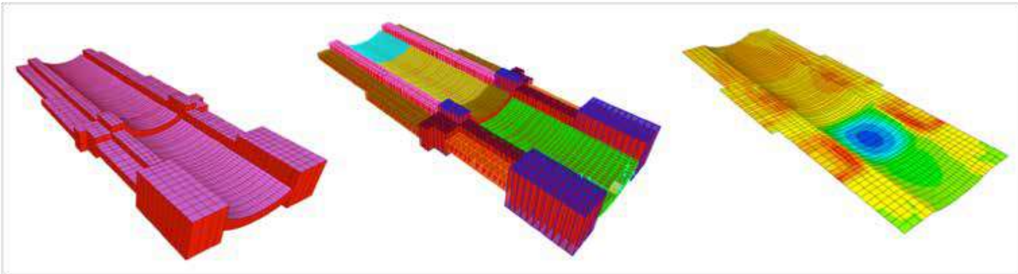

Figure 6. GFRP TBM cradle – FEM Analyses

4.1. Flexure

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

$$= 0.9 \cdot \eta_a \cdot \frac{\varepsilon_{fk}}{\gamma_f} \qquad (3)$$

where ηa and γm are above discussed and εtk 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 Mrd 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 Mrd is greater than 1.5 the flexural strength at first cracking Mcr. 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). 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 nf = EFRP/Ec, both for stage I (uncracked) and stage II (fully cracked). For quasi-permanent condition stresses in FRP elements should be σFRP ≤ ftd with ftd evaluated by (2) using the SLS coefficient.

(a) (b)

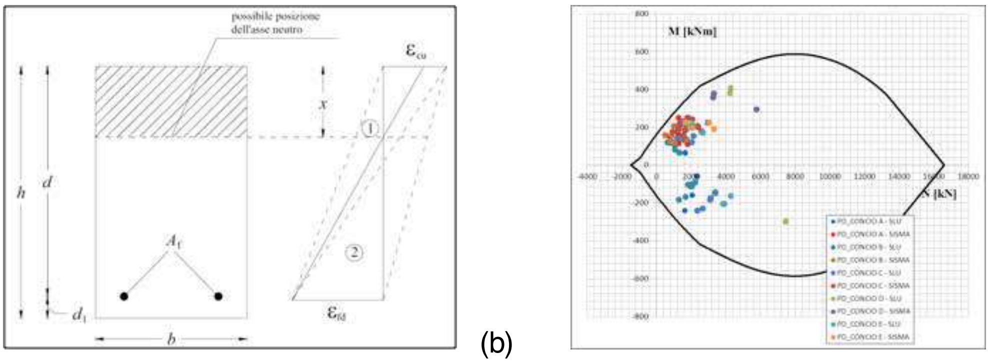

Figure 7. a) Bending rupture for GRFP r.c. b) ULS domain

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

$$_{\mathrm{td}} = \min\left\{V_{\mathrm{Rd,ct}}, V_{\mathrm{Rd,max}}\right\} \tag{4}$$

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

$$_{\mathrm{Rd,ct}} = 1.3 \cdot \left(\frac{E_f}{E_s}\right)^{1/2} \cdot \tau_{\mathrm{Rd}} \cdot k \cdot (1.2 + 40\rho_1) \cdot b \cdot d \tag{5}$$

thÆE_f, E_s = elastic modulus of FRP bars and steel (N/mm^2), τ_{Rd} = 0,25 $f_{ctd,}$ $k = (1{,}6 - d) \geq 1$ (d espressed i ı and $\rho_l = A_f/(b \times d) \leq 0{,}02$. If GFRP shear reinforcements are provided, shear resistance can be aluated as follows, considering the GFRP stirrups contribute $V_{Rd,f}$ (perpendicular stirrups):

$$_{\mathrm{td}} = \min\left\{V_{\mathrm{Rd,ct}} + V_{\mathrm{Rd,f}}, V_{\mathrm{Rd,max}}\right\} \quad V_{\mathrm{Rd,f}} = \frac{A_{\mathrm{fw}} \cdot f_{\mathrm{fr}} \cdot d}{s} \tag{6}$$

where Afw is the area of stirrups disposed with step s, ffr is the reduced design strenght = ffd/γfΦ (γfΦ is a partial factor that reduce the tensile strenght to take into account bending effects. Indicatively γfΦ = 2). The minimum shear reinforcement must be greater than 0.06 fck-1/2 bs/0.004 Ef with minimum equal to (0.35bs)/0.004Ef. Minimum stirrups: 3 for each meter and spacing less than 0.8 of the effective height.

4.3. Details

In beam elements the secondary reinforcements must be greater than 20% of the main reinforcements. The minimum bond length is equal to ld=0.1 σf×db with σf stress in the rebar and db 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 requested, 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.

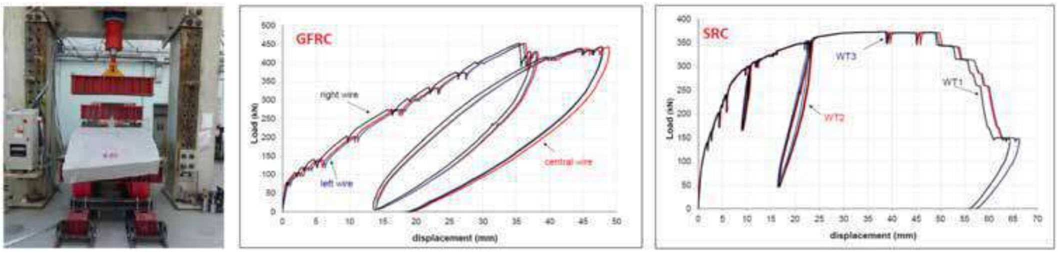

Figure 8. Bending rupture for GRFP and SRC

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 (Mr) 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 (Es /Ef ~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.

These aspects have been more accurately investigated as part of the “Research and Innovation program” (grant Agreement N. 672267) of the European Union’s Horizon 2020, under which several test have been performed by ATP S.r.l. at the “Laboratory of Material and Structures” of the University of Roma Tor Vergata in 2015-17. The aim of the research was to check the influence of the shape and typologies of the GFRP reinforcement cage on structural behaviour, so to define the most suitable solution from a technical and commercial point of view.

In underground tunnels, reinforcement with curvilinear configuration is required and the poltrusion process cannot be adopted; a special poltrusion process, named “pull-poltrusion”, has been developed, able to produce curvilinear bar with a constant and large curvature radius. This gives different options for the geometry of the reinforcement cage. Starting from a traditional steel reinforcement cage (SR cage) different solution have been investigated: the first solution (GFR-RR) consists of close “Ring Reinforcement” for both longitudinal and transverse reinforcement; the second one (GFRP-LR) is a “Lattice Reinforcement” and it is a combination of curvilinear bars, which are interlinked by means of lattice structure. The third cage is a “Wirenet Reinforcement” (GFRP-WR), in which the reinforcement cage consist of a wire net in extrados and intrados with C stirrups. The fourth cage uses a sand coating of the closed ring reinforcement in order to consider a better bond interface between concrete and GFR bars (GFRP-RR+B). The cages were composed by 12 bar, 12 mm in diameter, for the main longitudinal reinforcement and by 8 mm bars for the transversal reinforcements. All GFRP reinforcement cages were made with E-CR glass and vinyl ester resin, with tensile strength 2200-2600 MPa and E modulus equal to 81 GPa. The concrete compressive strength is 50 MPa. The segment, typical of a metro line, has a thickness of 300 mm, with internal diameter of 5800 mm and a width of 1420 mm.

The results of the tests are described in detail in Caratelli et al. (2017); in this program two testing set-up were carried out too: a bending test and a point load test aiming to simulate the TBM thrust. In Figure 9 the bending test results are reported: load versus displacement comparison. The failure mode and the maximum load are reported in Table 2.

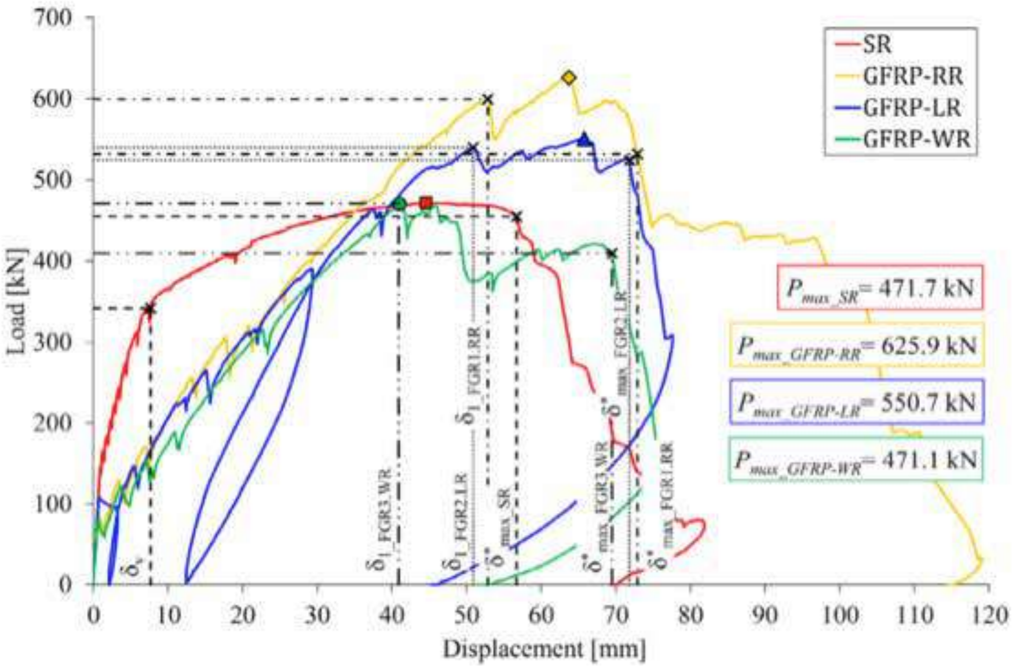

Figure 9. Bending test results for GRFP and SR

All precast segments show a comparable structural behaviour in term of maximum displacements, despite of the brittleness of the GFRP reinforcement. The GFRP-WR segment showed a failure load equal to the reference SR one, the other two prototypes, GFRP-RR and GFRP-LR, exhibited significant higher failure loads, with increase of about 32.7% and 16.7% respectively. Considering the three manufacturing process aspects (technical feasibility and commercial ones) the GFRP-RR represents the best solution among the prototypes tested.

Reinforcement	Failure mode	P_{crack} (kN)	w_{crack} (mm)	P_{max} (kN)	δ_{max} [(a)] (mm)	δ_y (mm)	$\delta_?$ (mm)	μ (–)
SR	Rebars rupture[(b)]	145.0	0.10	471.7	56.7	7.7	–	7.4
GFRP-RR	Rebars rupture[(b)]	88.0	0.50	625.9	72.9	–	52.8	1.4
GFRP-LR	Rebars rupture[(b)]	107.5	1.30	550.7	71.8	–	50.9	1.4
GFRP-WR	Rebars rupture[(b)]	71.0	0.05	471.1	69.5	–	40.9	1.7

[(a)] δ_{max} calculated at 0.85 P_{max}. In this case, no collapse was seen at that point.
[(b)] The failure occurred for the achievement of the tensile strength by the intrados rebars.

T le 2. The failure mode and the maximum load

(a)

(b)

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

6. CONCLUSION

The development and research into new materials led to an use of composite fibre-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. 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. In mechanized excavation method, the use of GFRP elements is very interesting both for provisional and long-term structure. The use of GFRP reinforcement for the diaphragms interested by TBM excavation is strongly recommended (the so called "soft eyes"); sometimes the launching ramps and cradles for TBM starting present provisional geometries which are in conflict with future part of the permanent structures, so that can be constructed employing GFRP bars, so to make easy its future demolishing. Precast reinforced segments with fiberglass bars could be used in highly aggressive environments, or in case of partial demolition of the lining structures, for example in achievement of niches, lay-by and by-pass. The use of GFRP nets is quite appropriate in protecting the edges of the segments; special rings, reinforced by GFRP bar, could be placed along the tunnel alignment, each 300-500 m, with function of "dielectric joint" towards stray currents. Experimental programs, by full scale tests and monitoring tests, have been performed in order to check structural behaviour in Serviceability and Ultimate Loads Conditions and define the best configuration for the GFRP reinforcement cage.

7. REFERENCES

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