The use of GFRP reinforcing elements & the mechanized excavation method

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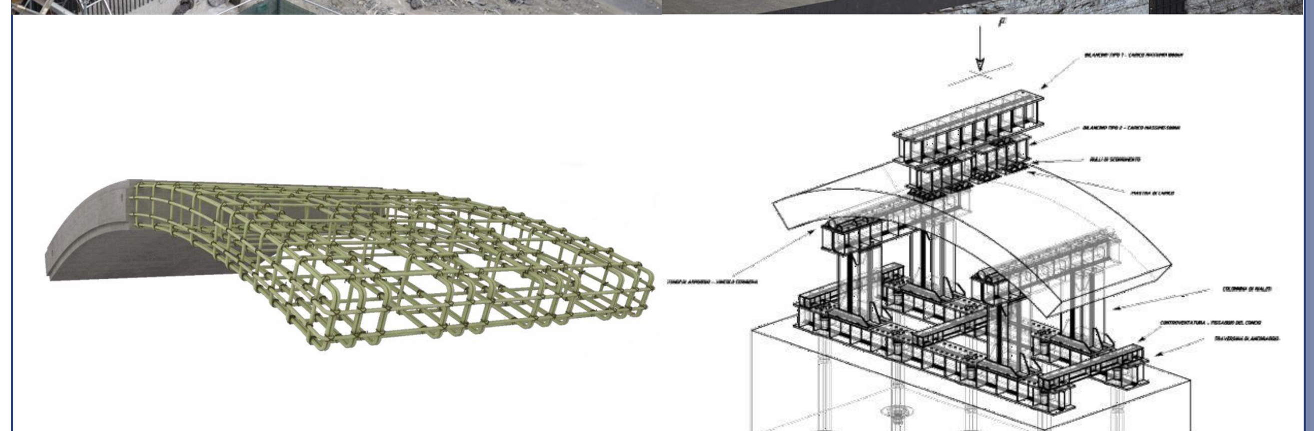
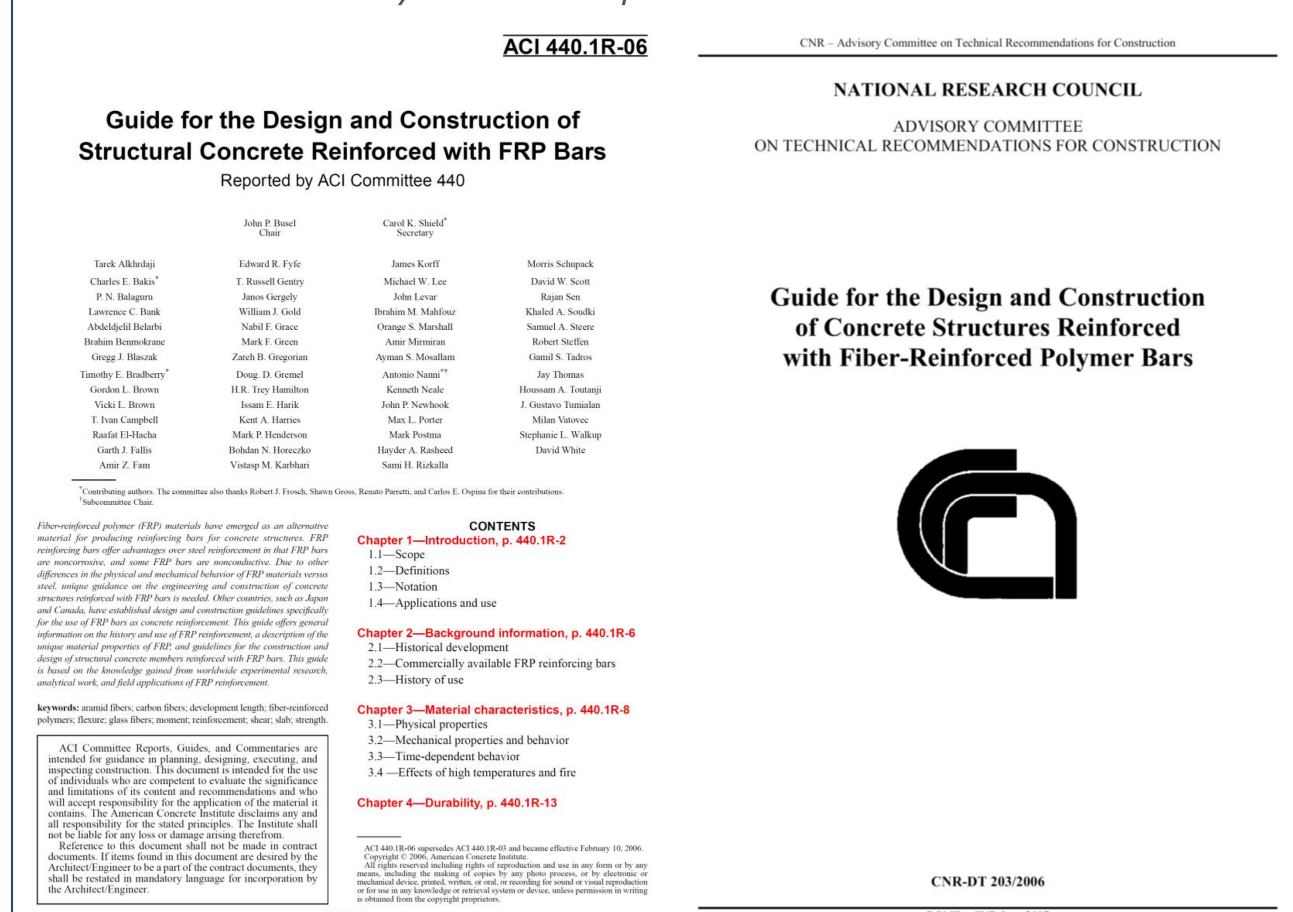
THE GFRP

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.



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.



ACI 440.1R-06

Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars

Reported by ACI Committee 440

CNR – Advisory Committee on Technical Recommendations for Construction

NATIONAL RESEARCH COUNCIL

ADVISORY COMMITTEE ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION

Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars

CNR-DT 203/2006

The behaviour of GFRP bars is depending on their physical and mechanical properties. 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.

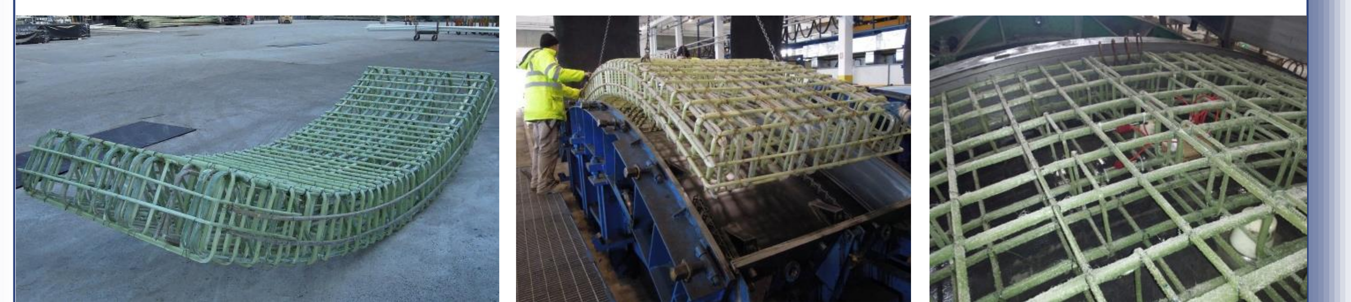
Properties	GFRP Rebar	Steel Rebars
Tensile strength (MPa)	700 ÷ 1200	350 ÷ 550
Elastic modulus (GPa) *	35 ÷ 50	210
Elongation (%)	1,5 ÷ 3.0	15 ÷ 30
Density (g/cm^3)	1,8 ÷ 2,1	7,8
Thermal conductivity (W/m°C)	0,25 ÷ 0,35	100 ÷ 250
Dielectric Strength (KV/m)	5 ÷ 15	---
Resistivity (Ωcm)	10000	9,68 × 10−11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

APPLICATION IN MECHANIZED EXCAVATION

The use of GFRP is very interesting in TBM tunneling owing to the several application which interest both the construction stage both the long term life of the tunnels.

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*
- *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*



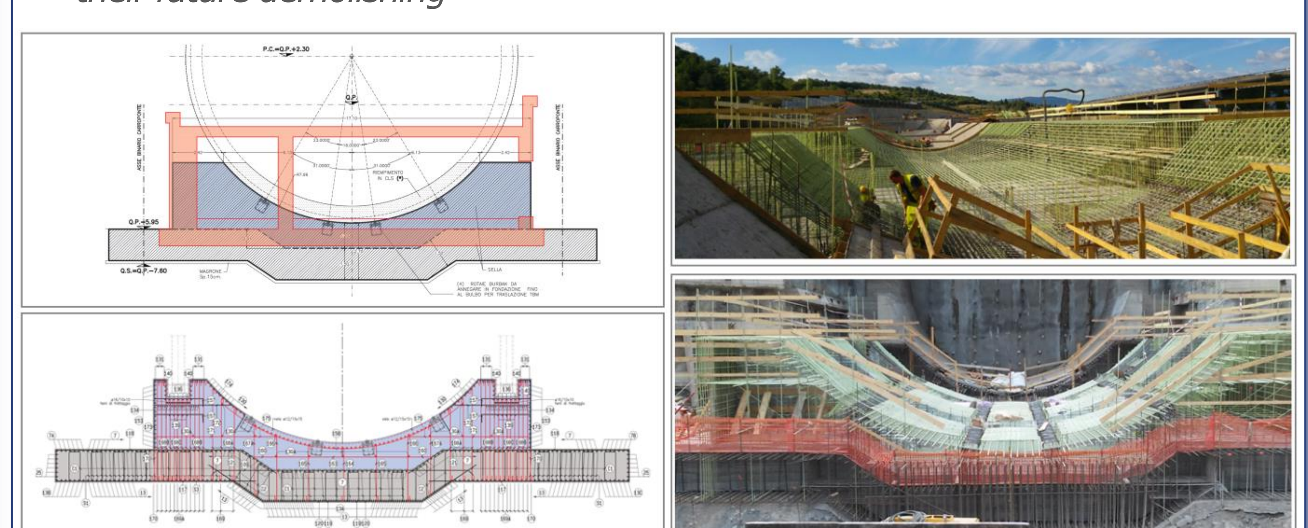
- *the use of GFRP nets is quite appropriate in protecting the edges of the segments, considering the possibility of reducing the values of concrete cover usually provided for metal reinforcements; this system is very useful to minimise the rupture which usually happen during TBM advance in handling and erection phases*

"Soft-Eyes"

- *GFRP bars could be used as 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, this way to be demolished without problems for TBM safety; this application is nowadays very frequent and represents a common practice*

Launching ramps and cradles for TBM

- *TBM starting elements 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*



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 guaranteeing the monolithic behaviour of the structural system. The static verification of the structures has been performed by FEM Analyses

DESIGN CRITERIA

ACI 440.1R-06 (2006) is a first reference code for designing GFRP reinforcements. 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:

$E_d \leq R_d$ — E_d = the design value of acting forces or effect

R_d = 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:

$X_d = \eta X_k / \gamma_m$ — X_k = characteristic value

γ_m = partial coefficient (ULS → 1.5, SLS → 1.0)

$\eta = \eta_a * \eta_l$ = conversion factor

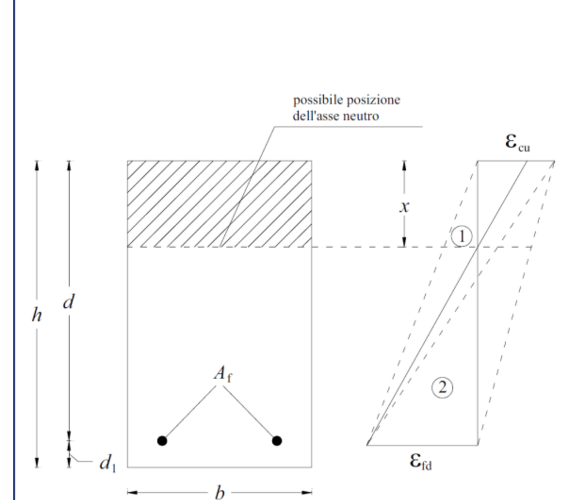
to takes into account the environmental and long-term aspects

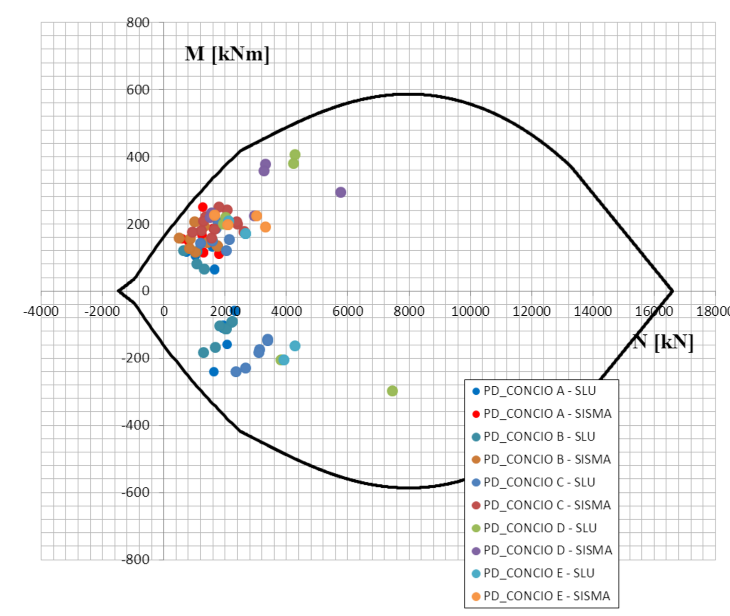
Flexure

According to the fundamental hypotheses above reported, the bending rupture occurs, 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:

$$\varepsilon_{fd} = 0.9 \cdot \eta_a \cdot \frac{\varepsilon_{fk}}{\gamma_f}$$

where η_a and γ_m are above discussed and ε_{fk} is the characteristic tensile strain, ranging between 1.5-3.0% (defined by laboratory tests). 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.
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





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:

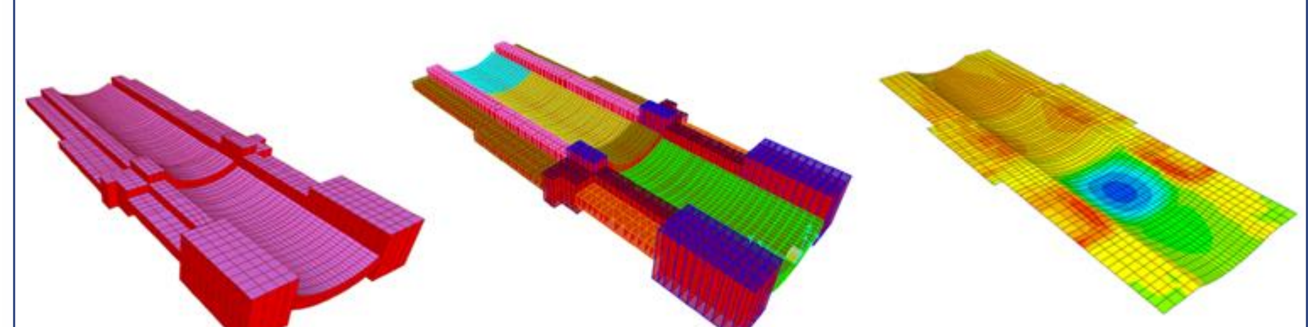
$$V_{Rd} = \min\{V_{Rd,ct}, V_{Rd,max}\}$$

$V_{Rd,max}$ concrete compressed rod resistance

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

If GFRP shear reinforcements are provided, shear resistance can be evaluated as follows, considering the GFRP perpendicular stirrups contribute $V_{Rd,f}$:

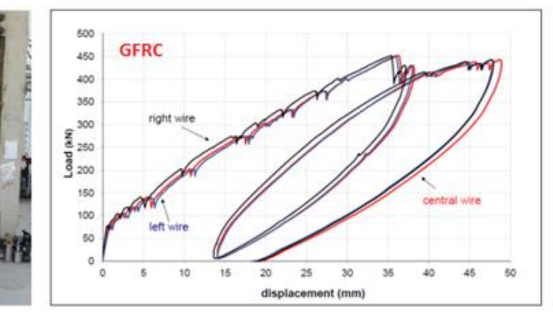
$$V_{Rd} = \min\{V_{Rd,ct} + V_{Rd,f}, V_{Rd,max}\} \qquad V_{Rd,f} = \frac{A_{fw} \cdot f_{fr} \cdot d}{s}$$



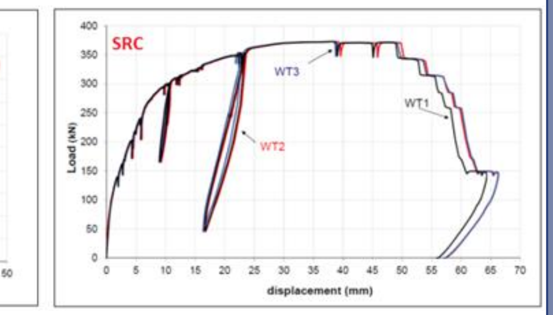
SRC vs GFRC - EXPERIMENTAL DATA

Several tests have been performed in order to check the experimental behavior of GFRP elements to compare with the predictive models and with the performing of the usual Steel RC structures. On September 2014, the 280 mm thickness segment used by "Metro Blu" for the construction of Metro Line 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.
Referring to the graph belowe, 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

Test set-up



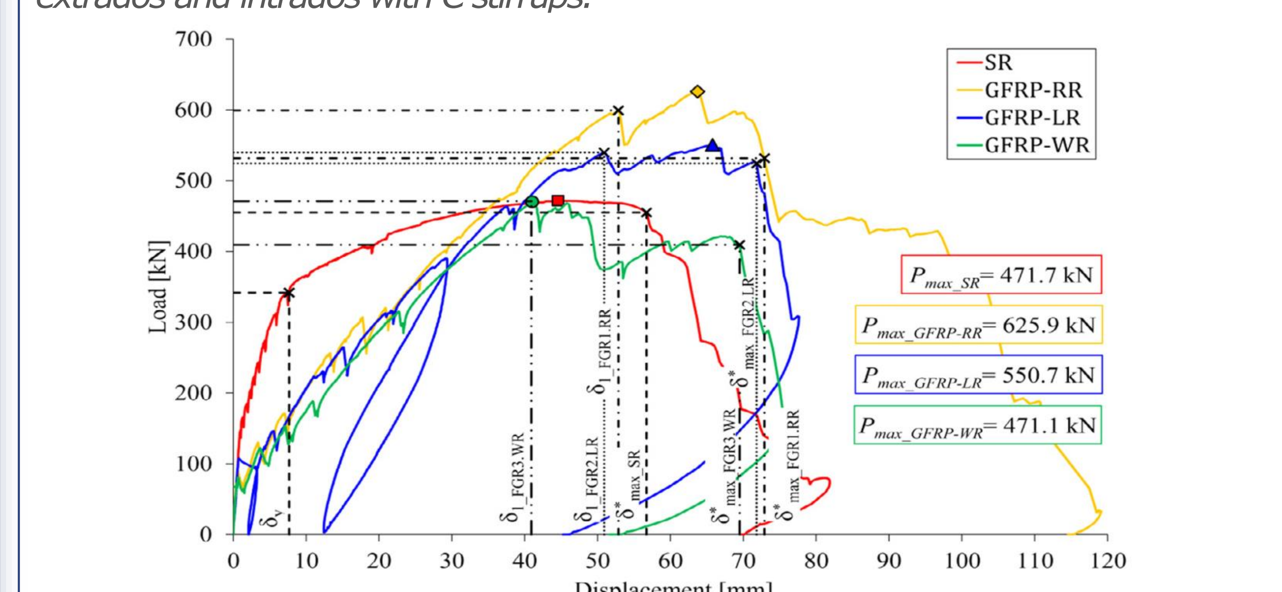
Bending rupture for GFRP reinforced segment



Bending rupture for STEEL reinforced segment

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.

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.



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)	δ_1 (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.

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