THE SUSTAINABLE TUNNEL REINFORCED WITH GLASS FIBER REINFORCED PLASTIC (GFRP) BARS

A. Focaracci

Prometeoengineering.it S.r.l., Rome, Italy

L. Rosati

Prometeoengineering.it S.r.l., Rome, Italy

ABSTRACT: Thanks to the exponential acceleration of technological progress in underground construction systems, it is reasonable to expect an increasing use of specialized tunnel boring machines and increasingly forward-looking research into innovative criteria and materials. The research is entirely aimed at making the execution of new works safer and more efficient, reducing the impact of the works on the environment and increasing their usability for society. The proposed innovation involves the complete (or partial) replacement of the current reinforcement of prefabricated lining segments (currently consisting of steel bars with improved adhesion) with equivalent reinforcement consisting of fiberglass elements (and possibly metal fibers). This innovation would allow for improvements in terms of safety, durability, and construction time and would ensure a significant reduction in CO2 emissions linked to the production of steel for the reinforcement of prefabricated segments. On average, a very large amount of steel (approximately 100 kg/m3) is required to reinforce prefabricated segments. Steel is an extremely energy-intensive material and certainly not negligible in terms of sustainability, due to the methods of procurement and transport of the material, as well as its processing in blast furnaces. In the current scenario, where international and national agreements exist to limit the production of pollutants, the use of more sustainable materials becomes (or should become) one of the criteria guiding design choices and processes.

This paper aims to present the introduction of GFRP bars in underground construction systems, demonstrating the results in terms of sustainability, safety, and durability, while optimizing the time and space required for the production of the segments.

1. INTRODUCTION

Rapid technological progress in the world of tunnelling continues to raise research and production standards to make the execution of new works increasingly safe and efficient, reduce the impact of the works themselves on the environment, and increase their usability for society.

In recent years, mechanized excavation technology using TBMs has increasingly established itself as a high-performance, innovative, and more versatile technology throughout the international scene for the excavation of full-section tunnels. This technology, which has become well-established in the excavation of natural tunnels in urban environments, has also become established over time for the excavation of natural road and rail tunnels in extra-urban contexts.

In Italy, since the use of the first EPB for the construction of the Milan railway link (1988), TBMs have been used in many contexts for road and rail tunnels.

The significant increase in the use of this technology goes hand in hand with the use and development of concrete linings made of prefabricated segments. Given the great advances in TBM excavation technology in recent years and the expected growth in the near future, it is necessary to identify innovative solutions for permanent linings as never before.

Nowadays, and increasingly in the future, it is of fundamental importance to develop technologies capable of speeding up the production of precast concrete blocks, reducing their costs, and improving the quality of the works in the project.

This topic is the subject of this article, as it proposes and analyses innovative and intelligent solutions for reinforcing the final prefabricated tunnel linings, enabling project targets to be achieved in terms of performance, product quality, and sustainability.

The innovative solutions proposed and analysed involve the use of GFRP bars, either on their own or integrated with other types of reinforcement (traditional rods, metal fibers) to create hybrid solutions. The reinforcements are arranged in such a way as to bear the stresses that arise in the lining segments during the different phases of the structure's life, taking into account the transitional configurations during installation, possible assembly defects, and long-term configurations

These solutions differ significantly from the use of reinforcement cages made entirely of steel rods, reducing the overall weight of the reinforcement, improving chemical and electrical resistance properties, allowing for more efficient arrangements of the resistant elements, and tending towards a more sustainable solution, in line with the current international scenario. The discussion remains at a qualitative level, albeit based on numerous numerical analyses and static checks, highlighting the advantages and critical issues of the various solutions.

Based on experience gained over the years, the main critical issues encountered in tunnels where prefabricated segments with integral steel rod reinforcement are used are persistent cracking and edge breakage, damage that requires repair work during construction, resulting in longer opening times and higher costs. These defects arise during the initial installation of the structural lining elements, which are immediately subjected to high stresses due to the TBMs advancing to guide and orient the machine. In many cases, the cracking can be repaired, but it is a defect that affects the durability of the structure.

2. FIBERGLASS

Fiberglass (FRP) is a type of plastic reinforced with glass fibers (GFRP - Glass Fiber-Reinforced Plastic), which allows the pultrusion of bars made with high-strength filaments impregnated with special thermoplastic or thermosetting resin, already used as reinforcement for the construction and repair of beams, columns, slabs, and other structural elements.

Figure1: GFRP Bars

Fiberglass reinforcement, composed of vinyl ester resin and glass, behaves in a completely different way, and in a certain sense opposite to that of metal bars: it is not affected by corrosion and, unlike metal bars, “suffers” more in alkaline environments, while it is completely inert in acidic or neutral environments. This means that, over time and as the concrete degrades, the durability of reinforcement with fiberglass bars increases. As for the potential for galvanic corrosion in the vicinity of overhead power lines and high-voltage cable ducts, this does not occur with fiberglass under any circumstances, as the material is completely insulating and insensitive to electric fields and electromagnetic waves.

The use of this material significantly increases the durability of the structure as a whole, avoiding an increase in the concrete cover (usually used to protect the metal reinforcement), which can lead to the rapid onset of cracks with consequent structural and aesthetic damage and costly restoration work.

The use of fiber-reinforced composite materials to replace steel in the construction of concrete structural elements is now widespread in many countries around the world, thanks to its properties:

Lightness: approximately 75% lighter than steel with equivalent performance, allowing for significant savings in delivery and handling;

Corrosion resistance: fiberglass reinforcement never rusts and is not affected by salt, chemicals, or alkalis;

Electromagnetic neutrality: it does not contain metal and does not interfere with the operation of sensitive electronic devices, being passive to stray currents;

Thermal insulation: high efficiency in resisting heat transfer.

Another key aspect is the short working life of steel reinforcement in segment structures. As is well known, segments are reinforced with a large amount of steel reinforcement to cope with long-term and short-term stresses (mainly during the installation of the segment, when it is subject to high stresses). This large quantity of material, which is extremely energy-intensive, is used for a very short period of time, constituting a “waste” and an example of incorrect use of a material's properties.

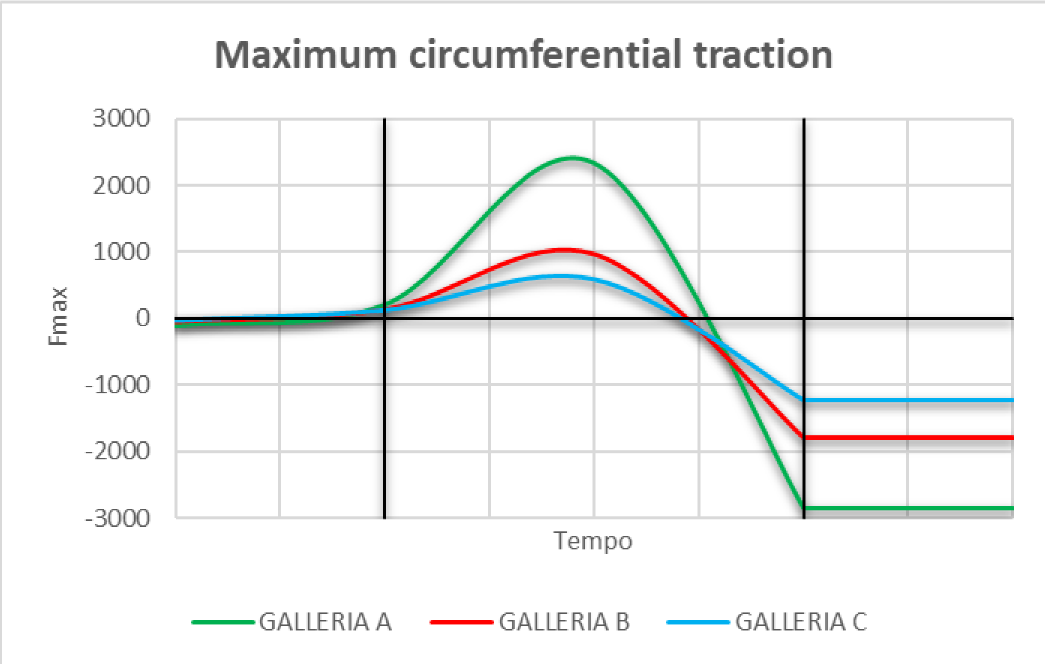

Figure2: Circumferential traction

A complete conversion from steel reinforcement to GFRP reinforcement guarantees greater sustainability for the project, a sustainability that can be found in the many characteristics that distinguish this material from traditional steel reinforcement.

First of all, replacing steel reinforcement with VTR reinforcement leads to a reduction in the weight of the reinforcement itself, resulting in faster installation and less use of operating machinery and labour. Reinforcing prefabricated segments requires a very high amount of steel on average (from 100 to 150 kg/m3), but switching to an entirely FRP option would reduce this by about two-thirds (to about 50 kg/m3). At the same time, working with this type of reinforcement would ensure greater safety for workers involved in the process and a consequent increase in efficiency. The partial or complete replacement of steel reinforcement with GFRP would lead to a reduction in CO_2 emissions in the production of bars, transport, and handling (as steel is known to be an extremely energy-intensive material, comparable in terms of CO_2 equals to GRP only if recycled steel is used). The use of fiberglass makes it possible to avoid the addition of certain concrete additives designed to protect the steel reinforcement from chemical attack.

Considering the production technologies currently in use (steel reinforcement vs. GFRP reinforcement), in terms of environmental impact on day zero, i.e., upon delivery of the work, here is a quick comparison carried out in recent years, according to the following parameters:

Ozone depletion;

Global warming;

Creation of photochemical oxidants;

Acidification;

Eutrophication.

Table 1: Environmental impacts

FRP-RC/PC environmental impacts						
ITEMS	PRODUCT STAGE	TRANSPORT TO JOB SITE	CONSTRUCTION	USE	EOL	TOTAL
Ozone depletion, kg	0,486	0,0197	0,0182	0,000359	0,0102	0,534
Global warming, kg CO2	883	81,2	83,9	8,69	34,3	1090
Photochemical oxidant creation, kg O3	51	9,43	6,4	422	4,39	71,7
Acidification, kg SO2	4,46	421	291	32	185	5,39
Eutrophication, kg N	1,46	92	150	13	42	1,76

CS-RC/PC environmental impacts						
ITEMS	PRODUCT STAGE	TRANSPORT TO JOB SITE	CONSTRUCTION	USE	EOL	TOTAL
Ozone depletion, kg	0,0619	0,0265	0,0242	0,00175	0,011	0,125
Global warming, kg CO2	1180	109	112	35,2	36,7	1480
Photochemical oxidant creation, kg O3	57	11,8	8,53	1,53	4,74	83,5
Acidification, kg SO2	4,48	495	388	121	199	5,68
Eutrophication, kg N	3,07	120	200	77	45	3,51

It is clear that GFRP reinforcement would therefore guarantee better results in terms of sustainability, safety, and durability, while also optimizing the time and space required for the segment manufacturing plant. Furthermore, the reduction in construction time and the elimination of any repairs after the segments have been installed is certainly a major advantage for the construction company.

3. INNOVATIVE SOLUTIONS

Below are the different solutions that have been analysed from a technical/structural and economic point of view, which constitute innovations in the field of prefabricated segment reinforcement. Below is a qualitative comparison based on the results of the analyses, highlighting the advantages and critical issues of the various solutions. The following considerations refer to a real case of a railway tunnel built using mechanized excavation, starting from the classic steel reinforcement solution (the characteristics of which are reported below) and developing innovative solutions. All the types considered are high-performance and innovative solutions, guaranteeing the same performance in terms of strength as a classic segment reinforced with B450C steel bars, but with better performance in terms of sustainability, material optimization, cracking, resistance to chemical attacks, and stray currents.

The following cases were analysed:

- A) Concrete segment with steel rod reinforcement.
- B) Concrete segment with integral GFRP reinforcement;
- C) Concrete segment with classic steel rod reinforcement + GFRP bars;
- D) Concrete segment with GFRP + steel fiber reinforcement.

1. CASE A

This reinforcement has been dimensioned to take into account the long-term and transient actions to which the segment is subjected during: breaking, handling, storage, installation, and lithostatic loads. The case in question refers to the section subjected to the greatest stress along the entire length of the planned tunnel. The layout of the reinforcement for the standard segment of the project in question is shown below.

2. CASE B

For the development of the solution, consisting of an entirely fiberglass reinforcement, steel-GFRP conversion was carried out considering bars and stirrups with improved adhesion, with bond >5 MPa on CLS C20/25. The GFRP bars exhibit elastic-linear behaviour up to failure, as required by Italian guidelines, and the reduction coefficients of CNR-DT 203/2006 are taken into account in the design.

The diameters of the steel rods are converted into appropriate GFRP bars (keeping the spatial arrangement unchanged), and all local and SLU and SLE resistance checks are performed for the various load configurations - transient and long-term.

From a structural point of view, the segment is reinforced with longitudinal reinforcement bars—along the tunnel axis—and transverse reinforcement bars, consisting of rolled steel bars. In addition to this main reinforcement, there is additional reinforcement that bears the tensile forces arising from the crushing of the segment during installation and handling, from radial compression during the useful life of the structure, and from any concentrated forces. It is the designer's responsibility to take into account all the design conditions and possible longitudinal and transverse contact defects that may occur during the construction of tunnels with prefabricated segments, particularly when using the now well-established universal ring technology.

There are also shear reinforcements consisting of stirrups, mainly on the perimeter of the segment, and, of course, construction bars.

The replacement of all this reinforcement with GFRP clearly results in a significant reduction in weight and difficulties associated with the processing of the bars, with the possibility of making the most of the new reinforcements by adapting them to their functions, without taking into account the limitations of steel.

3. CASE C

In the following solution, classic steel reinforcement is used to withstand the tensile stresses arising from long-term stresses, while GFRP bars are introduced to bear the stresses arising in the transitional phase. In particular, the positions introduced to bear the tensile stresses arising from the application of jack thrusts and incorrect positioning of the segments are replaced.

The positions introduced usually bear transitional stresses and satisfy the strength checks. The SLE and SLU checks remain the same as those adopted in case A (segment reinforced with steel rods only) for long-term stresses.

This solution minimizes the advantages of the full application of GFRP and maintains the critical issues of steel, as it is the predominant portion of the reinforcement cage.

4. CASE D

To overcome the critical issues of the solution consisting solely of metal fibers (fiber directionality, poor performance in the presence of concentrated stresses, and chemical and electrical attack ability), the following solution is analysed, in which GFRP reinforcement is present in addition to the steel fibers dispersed in the cement matrix.

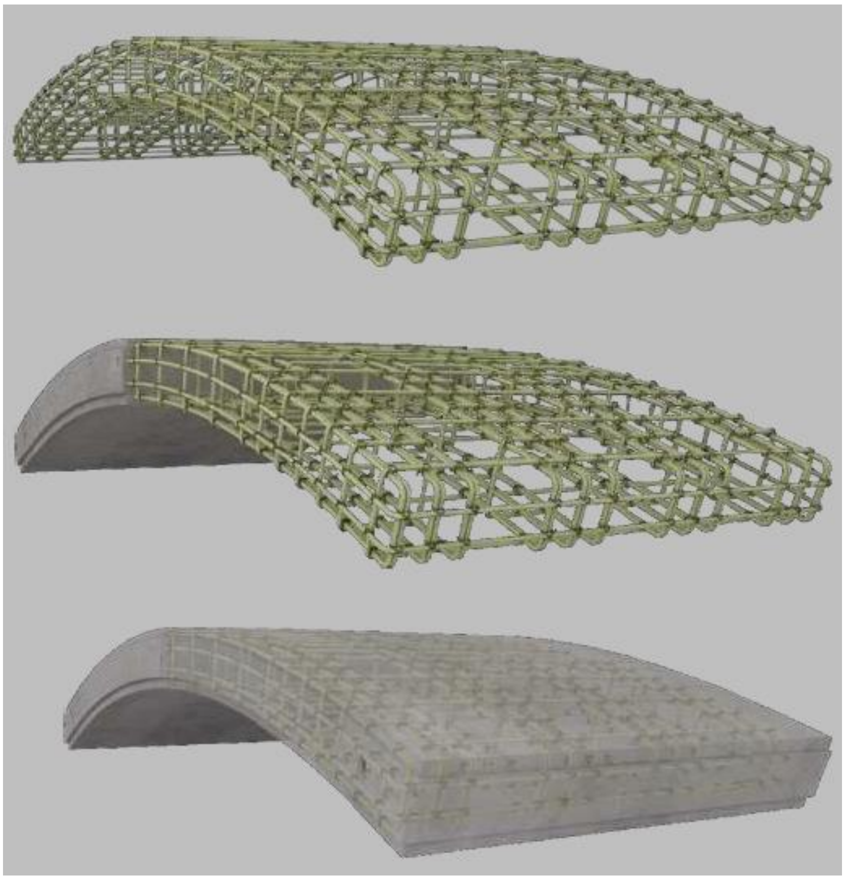

Figure3: GFRP Cage

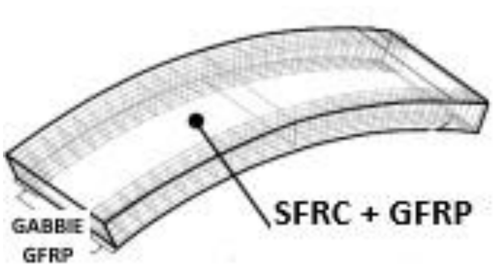

Figure 4: Hybrid solution

The VTR bars considered are similar (in terms of physical-mechanical characteristics) to those used in the development of solution B. The configuration of the bars in the segment is shown below:

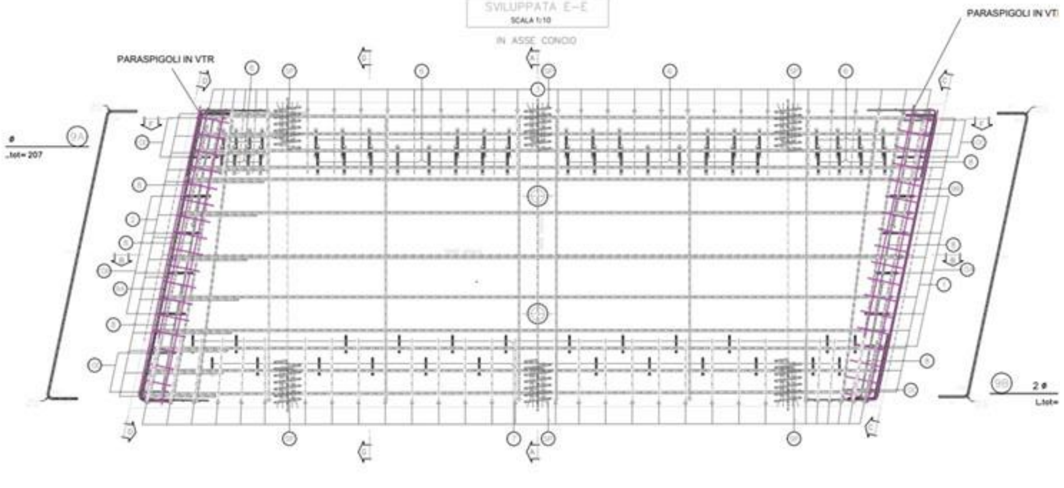

Figure 5: Hybrid solution

This solution guarantees the required performance, ensures the use of a more sustainable reinforcement overall, and is close to the cost of the classic all-steel solution.

In conclusion, of all the solutions highlighted, the latter is the most effective in all the aspects indicated, constituting a real solution for the structural reinforcement of precast segments.

The all-GFRP solution, despite offering many advantages, suffers from a technological gap compared to steel, resulting in a price that is not competitive with the classic or hybrid solutions highlighted above. It is hoped that progress can be made in this direction in the near future, focusing on the possibility of forming VTR reinforcement directly on site, thereby reducing overall costs.

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A. Focaracci
Prometeoengineering.it S.r.l., Rome, Italy
a.focaracci@prometeoengineering.it

L. Rosati
Prometeoengineering.it S.r.l., Rome, Italy
l.rosati@prometeoengineering.it