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REINFORCEMENT OF MASONRY STRUCTURES USING COMPOSITE MATERIALS

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ABSTRACT

The work carried out concerns the “strengthening of masonry structures using composite materials” with the aim of contributing to the study of the behavior of FRP materials in relation to application on masonry substrates degraded by interaction with the surrounding environment and capable of responding well to earthquakes.

The use of these fiber-reinforced composite materials represents an important technological innovation, increasingly adopted in professional practice; it is a technology now consolidated in applications on both reinforced concrete and masonry structures. It is precisely with a view to structural rehabilitation that this work aims to expose as clearly as possible the surprising, yet equally well-known, world of structural reinforcement using fibrous composite systems, i.e., materials composed of two components:

- the reinforcement, present in a discontinuous manner and characterized by high mechanical properties (carbon fibers, aramid, glass, etc.)

- the matrix, identifiable as a continuous element, usually mechanically weaker than fibers, but which performs two fundamental tasks: holding the reinforcement and the reinforced structural element together and transmitting stresses from the structure to the fiber.

The use of FRP (Fiber Reinforced Polymers) in civil engineering concerns, as already mentioned, essentially the restoration of degraded or damaged structures and

the static retrofitting of existing structures located in various seismic zones. In these sectors, it is evident not only the excellent static results that can be achieved with their use, but also the operational difficulties that would be encountered if intervention techniques that exploit traditional materials were to be used.

For the sake of completeness, it should also be noted that, in this context, now largely favorable to composites, new generations of reinforcements are now emerging. In addition to the already “classic” FRPs, made with carbon fibers, aramid fibers, etc., or glass fibers coupled with organic matrices (epoxy resins), there are FRCMs (fiber reinforced cementitious matrix), TRMs (textile reinforced mortars), and SRGs (steel reinforced grout), which exploit both the exceptional properties of newly developed fibers, such as those made of PBO (polyparaphenylene benzo isoxazole), and a material like steel, which, while common in the construction sector, is characterized by innovative processes that improve its mechanical performance. All these new types of composites, despite having been classified under such different names, are united by the element that allows them to function and adhere to the substrate: namely, the cementitious matrix.

In the work carried out, glass fiber reinforced plastic (GFRP) is used for structural consolidation. This material has excellent mechanical resistance and good toughness, as well as being affordable, a feature of considerable importance given that the specific intervention is a private structure. Regarding the approach to this topic, we first discuss masonry in general, its characteristics, classification, etc.; then, we delve into the details of composite materials,

their properties, characteristics, and the various investigation techniques; finally, the application part of the work is illustrated, in which the critical areas requiring intervention are specifically analyzed, a recovery plan is prepared.

Renovation, with the use of GFRP materials in some areas (where necessary), highlighting the results obtained from both the pre- and post-renovation phases.

Manual classification of existing masonry:

In the engineering literature, several authors propose alternative methods for describing existing masonry. In this study, an initial subdivision was made based on the resisting element, which resulted in the following types:

- stone masonry.
- fired brick masonry.
- unfired brick masonry.
- brick masonry.

This part of the intervention consists of an assessment of compliance with seven parameters characteristic of the rules of the art, namely:

- M.A. (mortar quality, contact between elements, wedges);
- P.D. (presence of diatonic);
- F.EL. (shape of the elements);
- D.EL. (dimension of the elements);
- S.G. (staggering of the joints);
- O.R. (horizontality of the rows);
- R EL. (adequate resistance of the elements).

The second part concerns which materials to use:

What are composite materials?

The term FRP is an acronym for Fiber Reinforced Polymer. FRPs belong to the broad family of “structural composites,” that is, materials (which also include reinforced concrete) that consist of two phases:

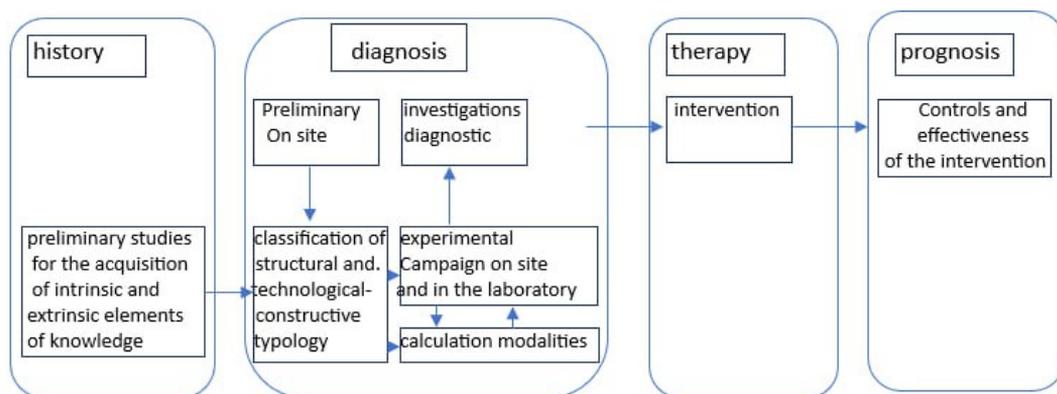
- a) the reinforcement, characterized by high mechanical performance.
- b) the matrix, identifiable as a continuous element and usually mechanically weaker.

The distinctive feature of structural composites (1) is that they provide better, or at least more “complete,” mechanical performance than that provided by the individual component phases.

In polymer matrix composites (FRP) (2), the matrix is generally made of an epoxy resin, while the reinforcements are made of fibers that can be carbon, glass, or aramid. FRPs are materials that have been used for several years in sectors such as naval, aeronautical, astronautical, and military, where they are exploited for their unparalleled specific strength, understood as mechanical tensile strength per unit of weight. The significant reduction in fiber costs, due to their greater diffusion and optimized production processes, has recently allowed the introduction of FRPs into the building construction sector as well.

The following provides essential information regarding composite materials, their components, and the methods of applying the reinforcements.

The recovery intervention project:



Confidence factors range from 1.00 to 1.35:

Level of knowledge	Geometry	Construction details	Material properties	Confidence factor
LC1	Structural survey	Limited in-situ checks	Limited in-situ investigations	1.35
LC2	Structural survey	Extended in-situ checks	Extended in-situ investigations	1.20
LC3	Structural survey	Comprehensive and exhaustive in-situ checks	Comprehensive and exhaustive in-situ investigations	1.00

Material	Young's Modulus E [GPa]	Tensile Strength σ_r [MPa]	Strain at Failure ϵ_r [%]	Thermal Expansion Coefficient ($10^{-6} \text{ } ^\circ\text{C}^{-1}$)	Density [g/cm^3]
E-glass fibers	72 – 80	3445	4.8	5 – 5.4	2.5 – 2.6
S-glass fibers	85	4585	5.4	1.6 – 2.9	2.46 – 2.49
Carbon fibers (high modulus)	390 – 760	2400 – 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon fibers (high strength)	240 – 280	4100 – 5100	1.6 – 1.73	-0.6 – -0.9	1.75
Aramid fibers	62 – 180	3600 – 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 – 3.6	40 – 82	1.4 – 5.2	30 – 54	1.10 – 1.25
Structural steel	206	250 – 400 (yielding) 350 – 600 (failure)	20 – 30	10.4	7.8

Comparison of the properties of the most common reinforcing fibers and matrices and of structural steel (indicative values):

Application Section:

A two-story masonry building constructed in the 1930s and 1940s and intended for residential use. The innovative part of this work concerns the existing surface where the reinforcing fibers will be applied.

Several tests were also carefully evaluated, specifically:

- a) three load tests on the floor with distributed loads to verify the bearing capacity and deformability of the structures.
- b) two ladder load tests to verify the bearing capacity and deformability of the structures.
- c) two masonry tests with flat jacks to verify the quality of the masonry and the stress state.

Specificity of the Interventions Completed:

- the May intervention was the strengthening of the external masonry piers, except for those on the first floor, through the application of a F.R.P. (Fiber Reinforced Polymer) composite mesh, made of AR (Alkaline Resistant) glass fiber.

Figures representing part of the intervention carried out:



Problem of masonry structures with low tensile and shear strength

Typical interventions:

- In-plane shear strengthening (vertical/horizontal strips or diffuse meshes)
- Out-of-plane strengthening (fabrics or meshes on one or both faces)
- Confinement of masonry piers

Composite material cladding and wrapping (FRP/FRCM)

The use of suitable composite materials (or other tensile-resistant materials) in the seismic strengthening of existing masonry elements (in fact) is aimed at the following objectives:

- • increasing the simple flexural or compressive flexural strength of piers and strips through the application of composites with fibers arranged in the direction of the

element's axis and, additionally, also in other directions.

- • increase the shear strength of studs and bands by applying FRP/FRCM with fibers arranged orthogonally to the element's axis (arranged according to the direction of the stirrups) and, additionally, also, in other directions.

- • increase the ductility of studs and bands by wrapping with continuous fibers arranged along the perimeter.

- • improve the efficiency of lap joints by wrapping with continuous fibers arranged along the perimeter.

- • prevent buckling of longitudinal bars subjected to compression by wrapping with

FRP/FRCM with continuous fibers arranged along the perimeter.

- • increase the tensile strength of nodal panels (intersection between studs and bands) by application of FRP/FRCM bands (3) with the fibers arranged according to the tensile isostatics.

For the safety checks of FRP-strengthened elements, the “Instructions for the Design, Execution and Control of Static Consolidation Interventions using Fiber-Reinforced Composites - Materials, reinforced concrete and prestressed concrete structures, masonry structures” (CNR-DT 200 R1/2013) (4) were adopted. Regarding the safety checks of FRCM-strengthened elements, the “Instructions for the Design, Execution and Control of Static Consolidation Interventions using Fiber-Reinforced Composites with an Inorganic Matrix” (CNR-DT 215/2018) (5) were applied, as well as the “Guidelines for the design, execution and maintenance of structural con-

solidation interventions through the use of FRCM reinforcement systems”, published by the Superior Council of Public Works.

STRUCTURAL DETAILS

The structural design was conducted in compliance with the structural details required by the Ministerial Decree of 2018, illustrated below. Compliance with these details can be seen not only from the drawings but also from the checks reported in the tables attached to this report.

CALCULATION TABLES (masonry data and data after reinforcement application).

For anything not expressly reported above, and for what concerns the numerical calculation data, please refer to the “Calculation tables” section, in summary:

Crack Pattern Analysis

The building has undergone consolidation work. Specifically, the internal plasterwork near all load-bearing walls and flooring at all levels have been demolished, and some excavations and/or trenches have been dug near the foundations.

The crack pattern is characterized by light, non-widespread damage, characterized only by fine or hairline cracks in the vertical structures, without significant material expulsion and/or dislocation of components.

Generally, for masonry buildings, a slight cracking pattern is not pathological; in fact, in such cases, no significant change in the structural strength is observed.

Legend

Characteristic Masonry

N _{id}	γ _k	α _{T,i}	E	G	C _{Erld}	Stz	γ _{m,v} / γ _{m,s}	f _{cm(k)} /	f _{tm(k)} /	f _{cm(k),o} /	f _{vm(k),o} /	τ _o /	μ	λ	TRT	
								f _{cd,v} /	f _{td,v} /	f _{cd,o,v} /	f _{vd,o,v} /	τ _{od,v} /			M	F
MURATURA IN TUFO ESISTENTE - (TUF)																
002	14 500	0,00001 0	1 410	473	60	F	2,50 2,00	2,00 0,59 0,74	0,040 0,012 0,015	2,00 0,59 0,74	0,100 0,030 0,037	0,040 0,012 0,015	0,40	20	1	2

“Fiber-reinforced material applied”

N _{id}	γ _k	α _{T,i}	E	G	Stz	σ _{lim,conv}	γ _m	η _{a,I} /	η _{a,E} /	η _{a,AA}	γ _{Rd,F}	γ _{Rd,T}	TP _{FRCM}	α _T
								η _{a,I}	η _{a,E}	η _{a,AA}				
GeoSteel G600 - tufo (a fasce) - (GeoSteel G600 - tufo (a fasce))														
006	16 000	0,000001	194 270	77 708	P	1 593,00	1,50				2,00	2,00	S	0,80
								0,90						
								0,80						
								0,70						

N_{id}

γ_k

α_{T,i}

E

G

Stz

σ_{lim,conv}

γ_m

η_{a,I}/ η_{a,E}/ η_{a,AA}

γ_{Rd,F}/ γ_{Rd,T}

TP_{FRCM}

α_T

- Material identification number in the corresponding materials table.
- Specific weight of the matrix.
- Thermal expansion coefficient.
- Normal elastic modulus.
- Shear elastic modulus.
- Type of condition:
 - F* = Existing (Strengthening);
 - P* = Design (New).
- Conventional characteristic tensile strength of FRCM.
- Partial safety factor.
- Environmental conversion factor:
 - η_{a,I} = “internal” exposure;
 - η_{a,E} = “external” exposure;
 - η_{a,AA} = “Aggressive Environment” exposure.
- Partial strength model factor:
 - γ_{Rd,F} = “Bending/Combined bending and axial load”;
 - γ_{Rd,T} = “Shear”.
- Fiber type:
 - S = “galvanized steel”;
 - PBO = “basalt and steel”;
 - GA = “glass and aramid”;



There are also some vertical or sub-vertical cracks in the walls at the intersection with the load-bearing walls connected between walls.

Conclusions

Based on this work, it has been found that, among the reinforcements of proven effectiveness and versatility such as FRP (Fiber Reinforced Polymer) (6), glass-based FRP (GFRP) also enters fully into the field of structural restoration and consolidation, a material which has a

excellent mechanical resistance (2-5 GPa), good toughness, low elastic modulus (70-80 GPa), medium density (2.5-2.8 gr/cm³), and affordable cost, in the case under study a notable improvement of the structure was found in response to the earthquake, the results obtained from the analysis(7) in non-linear static mode, highlighted an advantageous change in such a way as to cause all the analyses prescribed by the regulations to be verified so that the structure was able to withstand the projected earthquake, furthermore, the implementation of the aforementioned material was chosen, first of all as already mentioned, for its structural resolution capabilities, but also for the following intrinsic characteristics such as;

- good workability (epoxy matrices typically have difficulty working at temperatures below 10°C or above 30°C, as the curing process is severely affected);

- good fire resistance (epoxy matrices generally cannot withstand

- temperatures above 80°C to 110°C without softening and thus compromising the performance of the reinforcement);

- applicability on damp substrates (epoxy matrices require a perfectly dry substrate);

- allow walls to breathe and thus prevent the formation of surface condensation (epoxy matrices create an impermeable barrier to any fluid);

- workers do not require special respiratory protection or hand protection during installation (epoxy matrices can be toxic).

- glass fibers are more economical than other types of fibers, which is not to be underestimated, especially in public procurement.

Finally, the vast and diverse field of application of composite reinforcements is of considerable importance, highlighting what appears to be an excellent combination of respect for Italy's immense cultural heritage, represented by structures of rare architectural beauty, and the need to safeguard it by strengthening its framework without disturbing its essence.

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