Focussed on Steels and Composites for Engineering Structures

Visual Abstract

Effect of nylon fabric reinforcement on the mechanical performance of adhesive joints made between glass and GFRP.

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ABSTRACT. The use of reinforcements in adhesive joints makes the stress distribution more uniform, improving their mechanical performance and adhesion. The present paper aims to verify the effectiveness and efficiency of the insertion of nylon 6 fabric in the adhesive layer, to study their applicability and functionality in building components. The increase in stiffness achieved by applying nylon 6 fabric in the adhesive layer between glass and GFRP pultruded profiles and steel laminates applied to GFRP beams is investigated. Three different epoxy adhesives and one epoxy resin are used and compared. Three different types of tests are carried out in order to study the different properties of the reinforcement system: tensile tests on GFRP/GFRP single-lap adhesive joints, with and without nylon fabric reinforcement; tensile tests on double-lap adhesive joints between float glass and pultruded GFRP profiles reinforced with nylon fabric according to four configurations (in the middle plane of the adhesive layer, on the glass surfaces, on the GFRP surfaces, on both GFRP and glass configurations) to verify the influence of its position; three-point bending tests on long GFRP tubular profiles reinforced with steel plates and nylon fabric in different configurations, to study resistance to bending loads. The results from the experimental campaign show the effectiveness of the reinforcement system using nylon fabric 6. In general, both a reduction in ultimate strength and an increase in joint stiffness compared to unreinforced configurations are observed.

KEYWORDS. Nylon reinforcement; Reinforced adhesive joint; Adhesively bonded joints; Shear tests; Three points bending tests.

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INTRODUCTION

In recent years, GFRP (Glass Fiber Reinforced Polymer) pultruded profiles are increasingly used in different fields of application, thanks to various benefits such as reduced weight, ease of installation, low electrical and thermal conductivity, corrosion resistance and durability in critical exposure conditions [1–3]. These features configure GFRP profiles as a valid alternative to traditional materials in the field of civil engineering. Many applications see the use of GFRP in the structural field or in new building components [3–5].

At the same time, several factors such as their mechanical orthotropic properties [6], brittleness in bolted connections [7] and their Young modulus lower than other materials such as steel [3,8,9], make the application of GFRP profiles disadvantageous, especially when concentrated loads occur [10–12]. Moreover, the extreme sensitivity of GFRP to fire is a relevant problem. Therefore, notch sensitivity and low mechanical properties in shear of composites make traditional joints unsuitable, favoring the adhesive ones [13,14]. Recently, an increase in the use of structural adhesives in the civil engineering field could be observed. The widespread use of adhesives is the consequence of their reduced weight, their capacity to distribute stresses in a more uniform and contained way and to allow more flexibility in the realization of connections and the possibility of bonding different materials. Adhesive joints also avoid concentrated stresses, which are typical of traditional joining methods (e.g., bolted joints).

The new capabilities of structural adhesives led to the development of hybrid structures made of glass and steel [15]. An extensive experimental campaign demonstrated the effectiveness of an adhesive joint between GFRP profiles [16] and between GFRP and steel adherends [17].

Munafò et al. [18] demonstrated through experimental studies the compatibility of adhesive joint made between glass and GFRP adherends, even under different exposure and aging conditions, by observing that the best adhesion occurs with epoxy adhesives. In fact, the epoxy adhesive was the best in terms of bearing capacity and durability.

To date, however, few studies are still available to evaluate the compatibility of hybrid glass-GFRP adhesive joints. This is partly due to the wide variation of the physical properties of the adhesives along with their nonlinear properties and unknown behavior during their service life.

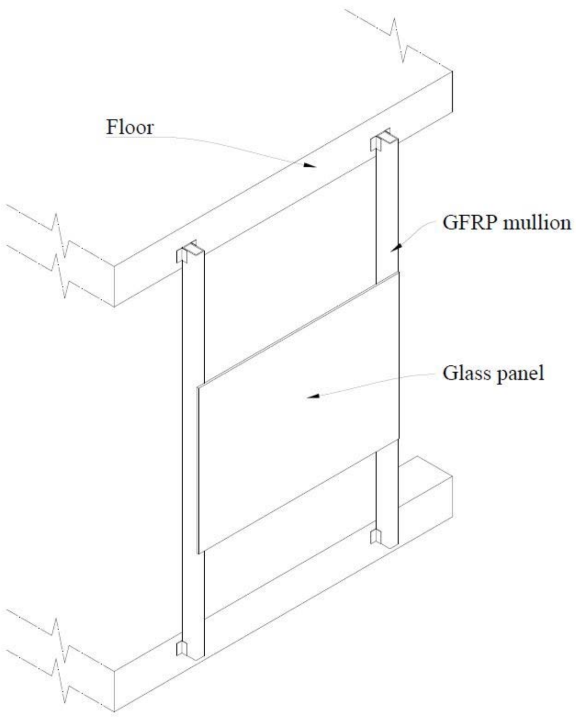

Figure 1: Curtain wall mullion scheme, axonometric view.

One of the objectives of the present paper is the development of a curtain wall construction technology using GFRP mullions (Fig. 1), illustrated in the patent n. 102020000025636 (inventor Prof. Munafò). This solution for curtain walls involves bonding thin steel plates (2 mm) to the extrados of GFRP beams to stiffen the profile and allow the glazed panels to be fixed mechanically using bolted joints. These panels are made of GFRP profiles positioned inside the glazing unit and joined to the frame by means of structural adhesives. The aim of the invention is, on the one hand, to allow the use of large, glazed surfaces (e.g., 3.50 × 3.00 m^2) and, on the other hand, to simplify the assembling technique of commercial mullions, thanks to the characteristic of the material which allows the elimination of the thermal bridge (as stated in the Invisible Window patent, EP.3071775B1.

Another aim is to assess the compatibility of the bonding system between GFRP and float glass by verifying the mechanical contribution of nylon reinforcement to the joint performance in terms of stiffness. The mechanical performance of adhesive joints in unreinforced configuration is investigated and compared to that of reinforced ones. The use of adhesive bonding enables structural cooperation between glazing panels and substrate elements [19], making it possible to reduce the cross-section of the load-bearing substrate element and to guarantee high mechanical performance. This objective seeks to meet market research, which is oriented towards the assembling of large, glazed panels supported by structural elements with reduced dimensions.

Numerous techniques, aimed at reducing stresses concentration and increasing cross-resistance [20], were developed in terms of material design and joint geometry.

Amiri et al. [19] investigated the effect of the geometrical parameters of the "button-shaped" edge reinforcement experimentally and numerically. Different parameters such as the radius and the height of the button, the geometric and mechanical properties of the adhesive were considered. It was observed that by increasing the radius up to six times the thickness of the adhesive, it was possible to increase the resistance of the joints significantly (up to 300%). Nosouhi et al. [20] studied experimentally the effects of the geometric parameters of wavy edges on the strength of adhesive joints. For the optimal configuration, the corrugated edge joint offered 32% more strength than the normal single-lap joint. Davies et al. [21] investigated the use of metal particles to reinforce single-lap adhesive joints. This reinforcement highlighted its effectiveness by increasing the tensile strength. Further studies [22] tested the effect of adhesive joints reinforcements experimentally, using steel wires positioned inside a brittle glass matrix, studying their mechanical behavior through mathematical models. Kaji et al. [23] experimented with a reinforcement technology using steel wires inside the adhesive layer. A significant increase in joint strength was observed (up to 90%). Morgado et al. [13] analyzed the mechanical performance of single-lap joints in CFRP with aluminum reinforcements. An increase in joint strength and absorbed energy was observed. Zhu et al. [24] demonstrated the effectiveness of metallic solder balls reinforcement in the adhesive by improving the distribution of transversal stresses, associated with an increase in strength and absorbed energy.

From state-of-the-art, three epoxy adhesives and one epoxy resin were selected, which were more suitable for bonding different materials such as glass, GFRP pultruded composite material, and steel [17]. In order to assess the mechanical compatibility between GFRP/float glass adherends in adhesive bonding and to study the variations in stiffness provided by nylon reinforcement, different types of specimens were assembled.

In the first phase, single-lap joints were manufactured, characterized by pultruded adherends bonded with two-component epoxy by interposing – or not – the nylon 6 fabric in the adhesive joint, to verify its effectiveness. Subsequently, double-lap joints between glass and GFRP adherends bonded with three different epoxy adhesives by applying nylon fabric 6 inside the adhesive layer according to four positions (in the adhesive midplane, on the glass surface, on the GFRP surface and on both surfaces), were assembled and tested to evaluate its effectiveness as the position of nylon fabric changes. Finally, tubular squared long beams in GFRP pultruded profiles, characterized by the application of nylon on the lower web, steel plate and combined reinforcement made of nylon and steel plate both by resin and by epoxy adhesive were tested.

For the first two types of samples, shear tests were carried out, while the beams were tested in three-points bending tests. The mechanical parameters analyzed are the stiffness and ultimate strength of the joint. In the particular field of application considered, the resistance to wind loads, standardized by UNI EN 12210 [25] defines the capacity of the window, subjected to strong pressures and depressions (up to 2000 Pa), to undergo admissible deformations within which the element maintains its functionality

MATERIALS AND METHODS

The present study aims to evaluate the effect of nylon 6 fiber reinforcement on the mechanical performance of GFRP-glass adhesive joints and on the flexural performance of GFRP profiles reinforced with steel plates.

Experimental tests include:

- shear tests on GFRP-GFRP single-lap adhesive joints assembled with epoxy resin (EPXRN) and reinforced with nylon 6 fabric;

- shear tests on GFRP-float glass double-lap adhesive joints assembled with three different commercial epoxy adhesives (EPX1, EPX2, EPX3); in detail:
  - unreinforced joint;
  - reinforced joint with nylon 6 fabric applied on the pultruded profile;
  - reinforced joint with nylon 6 fabric applied on the glass;
  - reinforced joint with nylon 6 fabric applied both on the glass and on the GFRP profile;
- three-points bending tests on tubular long GFRP beams, in detail:
  - unreinforced GFRP beam;
  - GFRP beam reinforced with steel plate applied with EPX1 adhesive;
  - GFRP beam reinforced with steel plate applied with EPX1 adhesive and reinforced with nylon 6 fabric;
  - GFRP beam reinforced with steel plate applied with EPXRN resin;
  - GFRP beam reinforced with steel plate applied with EPXRN resin and reinforced with nylon 6 fabric.

Shear tests on single-lap and double-lap adhesive joint specimens, assembled with GFRP profiles adhesively bonded on float glass, are carried out according to ASTM D3528-16 [26]; the three-point bending tests on tubular pultruded beams are carried out according to UNI EN 13706-2.
Through these tests the effectiveness of the adhesion between adherends and adhesives is studied by comparing shear strength, shear stress at failure, ultimate displacement, and stiffness of the joints.

Material Properties

In this study four different materials were used: transparent float glass, manufactured by Vetromarche (Italy), GFRP pultruded profiles manufactured by Fibrolux (Germany), S275JR steel plates manufactured by Termoforgia (Italy), and nylon 6 fabrics manufactured by Lazzati Group (Italy). The properties of the materials, as reported by the manufacturers in their technical sheets, are reported in Tabs. 1 and 2.

GLASS		STEEL PLATES*				GFRP PROFILES**		
E_t (GPa)	σ_t (MPa)	E_t (GPa)	σ_{ys} (MPa)	σ_t (MPa)	ε_t (%)	E_t (GPa)	σ_t (MPa)	ε_t (%)
75	40	210	326.7	385.5	29.1	26	400	1.5

*according to EN 10025-2:2004
**according to EN 755-2

Table 1: Technical and mechanical parameters of the adherends, reported by manufacturers.

Nylon 6	
Type	A
Dtex at brill (kg/bave)	0.840/96
Wires	5600
Mechanical stop	7.50
Fabric armor	Tela
Weight (kg/m)	0.0335
Thickness (mm)	0.24

Table 2: Mechanical parameters of the adherends, of the nylon 6 reinforcement as reported by manufacturer.

Four commercial two-component structural epoxy adhesives for the adhesive joints between glass and GFRP were used. Three types of epoxy adhesives (EPX), namely: 3M™ Scotch-Weld™ Epoxy Adhesive 7260 B/A [27] (EPX1), Gurit Spabond 340 LV [28] (EPX2), Gurit Spabond 345 [29] (EPX3), and an epoxy resin, namely Kimitech EP-TX [30] (EPXRN) were selected. The relative technical and mechanical characteristics reported by the manufacturers are summarized in Tab. 3.

Adhesive	EPX 1	EPX 2	EPX 3	EPXRN
Chemical base	Two-part epoxy	Two-part epoxy	Two-part epoxy	Two-part epoxy
Consistency	Controlled flow	Thixotropic Paste	Thixotropic Paste	Thixotropic Paste
Wt (min)	90 ÷ 300	-	-	15 ÷ 45
At (°C)	15 ÷ 25	15 ÷ 25	15 ÷ 25	> 5
St (°C)	-50 ÷ 120	< 80	< 80	10 ÷ 35
τ (MPa)	33.50*	(24.9 ÷ 30.7) *	(29 ÷ 36) *	6
σt (MPa)	-	-	-	6
Et (MPa)	3000	1800	-	5000
εt **(%)	3	-	-	-
Use	Structural	Semi-structural	Semi-structural	Semi-structural

* On aluminium-steel adherents
**At failure

Table 3: Technical and mechanical parameters of the adhesives reported by the manufacturers.

Experiments

Single-lap shear tests

Shear tests are carried out to evaluate the effectiveness of the adhesive joint between GFRP adherends and to verify the mechanical contribution of the nylon reinforcement applied in the middle plane of the adhesive layer. For each configuration three specimens were assembled and tested.

The geometry of the specimens was manufactured according to ISO 4587 [24]. The adherends had a width of 25 mm and a length of 100 mm; the overlap length was 12.7 mm. The thickness of the adherends was 5 mm. The thickness of the adhesive layer varies from 2 to 4 mm for unreinforced and reinforced joints, respectively. The geometry of the specimens is depicted in Figs. 2-3. The nylon fabric was first manually cleaned in order to remove any impurities (e.g. dust particles), dried and brought to environmental conditions at the time of the bonding phase. The surfaces of the GFRP adherends were treated in the bonding region by manual abrasion with sandblasting paper and degreased with acetone and isopropyl alcohol.

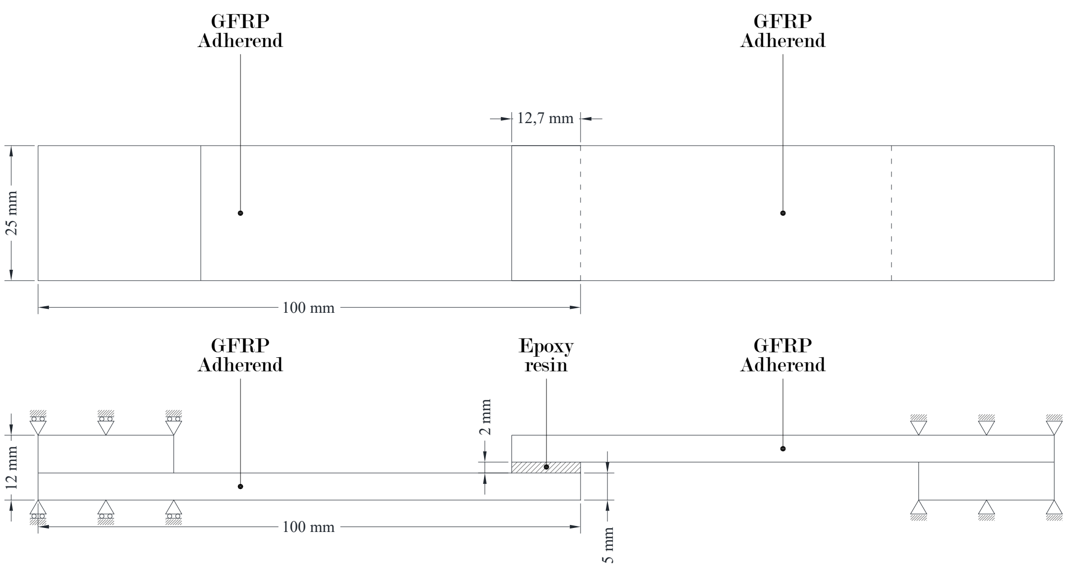

Figure 2: Unreinforced Single-lap specimens' geometry (mm), section view and plan view.

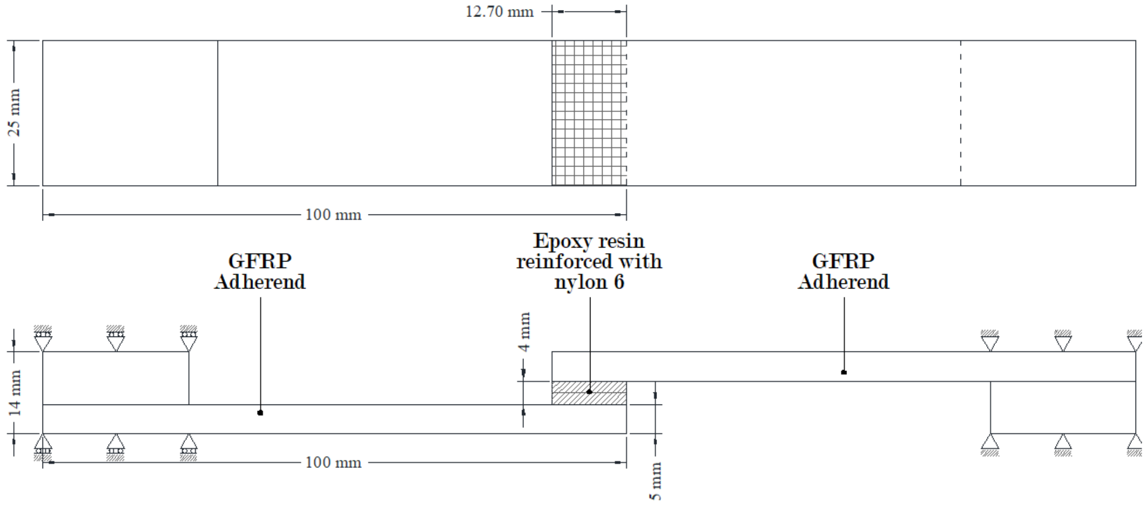

Figure 3: Reinforced Single-lap specimens' geometry (mm), section view and plan view.

All tests were carried out with a Zweick/Roell Z050 testing machine of 50 kN capacity under displacement control. Fig. 4(a-b) shows the setup of the tensile test, with the specimen subjected to shear test. The load was applied at the slow rate of 1.25 mm/min in laboratory conditions of 22 ± 1 °C/ 43 ± 3% RH measured using a datalogger. Load, displacement, and strain were measured by transducers connected to the machine.

Figure 4: Experimental setup: shear test on GFRP-GFRP single-lap joints (a), shear test on GFRP-glass double-lap joints (b), bending test on GFRP steel squared tubular beams (c).

Double-lap shear tests

Double-lap adhesive joints were manufactured according to ASTM D3528-16 [31]. Three samples were assembled for each type of adhesive and nylon reinforcement position (on GFRP surfaces, on glass surfaces, middle position, on glass and GFRP surfaces). Fig. 5 illustrates the geometry of the specimens with EPX1, EPX2, EPX3 adhesives. GFRP adherends had section 25×5 mm^2 and 100 mm in length; float glass panels were 200×100 mm^2 and 5 mm thick. The area of the adhesive layer measured 25×12.70 mm^2 and the thickness was 0.30 mm, as recommended by the manufacturer for unreinforced specimens [27–29]. In nylon-reinforced configurations, the thickness was increased to 2 mm to allow the reinforcement application.

The assembly phase of the specimens took place under laboratory environmental conditions (20±1 °C/50±5% RH, measured using a datalogger). As recommended by the manufacturer, the surfaces of the GFRP adherends were treated near the adhesive joint by manual abrasion with sandblasting paper and degreased with acetone and isopropyl alcohol. The nylon fabric was first cleaned manually, dried and brought to laboratory environmental conditions before the bonding phase. All specimens were labeled according to the adhesive used and cured in laboratory conditions for 30 days before testing, as recommended by manufacturers [27–29].

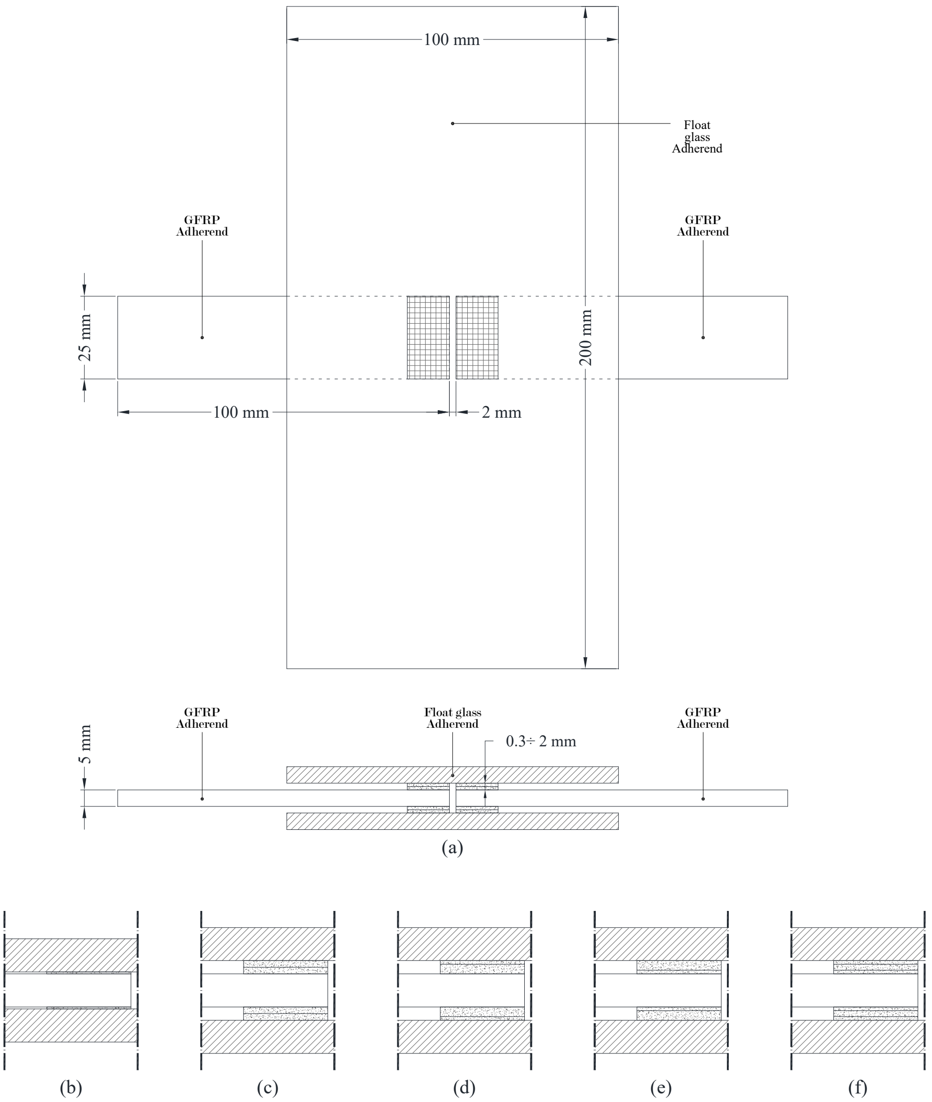

Figure 5: Double-lap specimens' geometry (mm), section view and plan view (a); detail of unreinforced joint (b), adhesive reinforced joint with nylon in middle position (c); adhesive reinforced joint with nylon on glass (d); adhesive reinforced joint with nylon on GFRP (e); adhesive reinforced joint with nylon both on glass and GFRP (f).

Three points bending tests

Three points bending tests – according to UNI EN ISO 14125 [32] – were performed to simulate the wind load to which the structural parts of a facade or windows are subject. The experiments involved the combined use of steel plates and nylon 6 reinforcements to increase the stiffness of the GFRP element. The external beam section in GFRP was 50 × 80 mm^2, 5 mm thick and 1000 mm long. The steel plate was made of S275JR steel with a 2 mm thickness (Fig. 6). The reinforcements were applied - for each type of configuration - along the entire length of the beam.
The adhesives used for the application of reinforcements are the EPXRN resin with a thickness of 2 mm and the EPX1 adhesive, applied with a thickness of 0.30 mm, as recommended by manufacturers. The specimens were prepared by sandblasting and then cleaning the bonding regions with denatured isopropyl alcohol. The nylon fabric was prepared according to the methods illustrated for the previous tests.
Fig. 4c illustrates the setup of the three-points bending test; the displacement was applied with a speed rate of 3 mm/min. The displacement was measured through DIC technology. The Digital Image Correlation is a three-dimensional measurement technique using two or more cameras. This method allows the analysis of deformations and three-dimensional displacements using non-flat objects.

The 3D DIC method consists of three main phases: i) preliminary preparation of the test specimen and setup of the test setup; ii) acquisition of the images during the experimental test; iii) analysis of the images acquired by a correlation program aimed at measuring the displacement and deformation field.

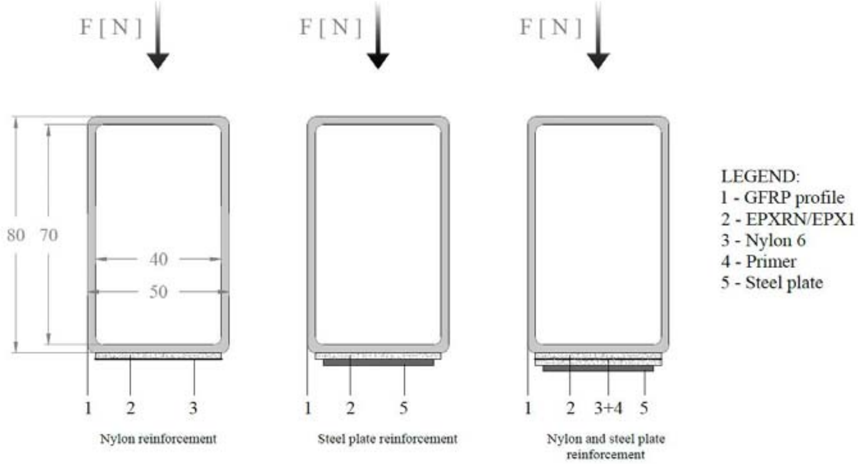

Figure 6: GFRP-nylon-steel squared tubular specimens in three different configurations.

RESULTS AND DISCUSSION

In this section, the mechanical performance and failure modes of the tested specimens (single-lap GFRP-GFRP joints, double-lap GFRP-glass joints, three points bending tests on GFRP squared tubular long profiles) are shown in both the unreinforced and the reinforced configurations. The results are subdivided according to the type of test.

Shear tests on single-lap joints

Fig. 7 shows the comparison between the load-displacement graphs for the single-lap GFRP-GFRP joints assembled using EPXRN resin and the same joints reinforced with nylon 6, applied in the midplane of the adhesive layer.

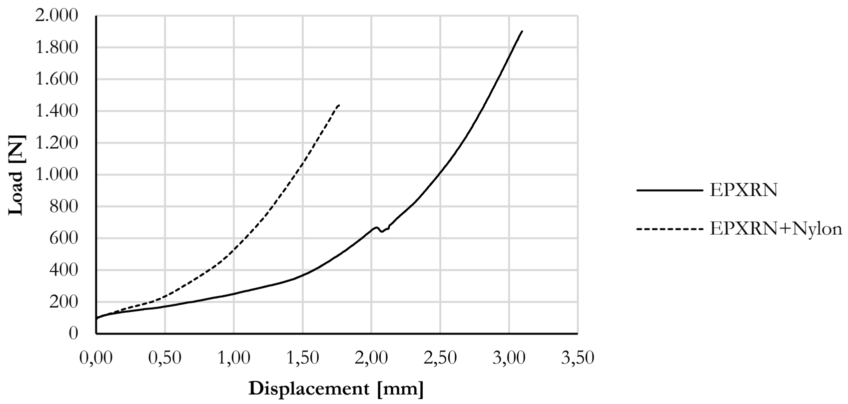

Figure 7: Representative load-displacement graphs of GFRP-GFRP unreinforced and reinforced adhesive joint made with epoxy resin EPXRN.

Adhesive	Nylon reinforcement	F_{max} (N)	τ_{max} (MPa)	γ_{max} (%)	s* (mm)	k_1** (N/mm)	k_2** (N/mm)
EPXRN	-	1818±244.95	5.73±0.77	0.96±0.18	3.04±1.10	283.61±126.99	1067.01±100.49
EPXRN	Middle	1665±584.32	5.24±1.84	0.78±0.05	1.99±0.20	332.01±300.26	1126.70±302.03

* at failure

** obtained by bilateral approximation.

Table 4: Mechanical parameters of the adhesives reported by the manufacturers.

Tab. 4 shows the average values of the ultimate load (N), the ultimate displacement (mm) and stiffness (N/mm) of single-lap specimens both unreinforced and reinforced, subjected to shear test. Due to the non-linearity of the curves, the evaluation of the joint stiffness was carried out by means of a bilinear approximation of the experimental curves (Fig. 8). The best stiffness (k) performance is observed in the reinforced configuration with the nylon 6 fabric applied in the midplane of the resin layer, although failure occurs at a lower load value than the unreinforced specimen. The insertion of the nylon reinforcement results in an increase in stiffness in both the segments of the curves. Stiffness increases of +17% and +6% were recorded in the first and second segments, respectively. In addition, a slight decrease (-8.42%) in the ultimate load of the reinforced configuration, compared to the unreinforced one could be observed. Therefore, the insertion of the nylon fabric inside the adhesive layer leads to an increase in the overall elastic modulus of the joint, making it stiffer, reducing the ultimate load.

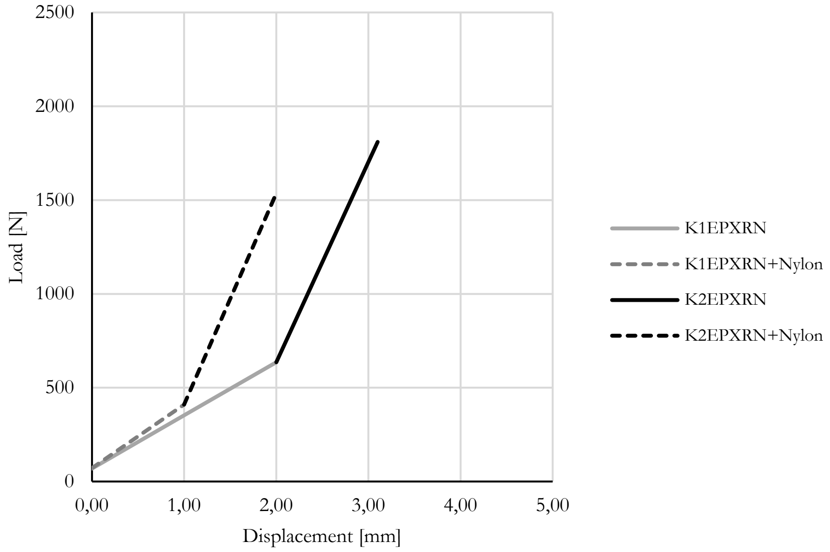

Figure 8: Bilinear approximation of load-displacement graphs and evaluation of the joint stiffness.

According to ASTM D5573-99 [33] standard, at the end of the test, it was observed that the failure modes of all the specimens realized with EPXRN resin, with and without nylon, are of the LFTF type (Light-fiber-tear-failure), i.e. there is a few glass fibers of GFRP transferred from the adherend to the interface of the adhesive (Fig. 9). In fact, in the bonding region (dotted in red), the specimens show a different color of substrate material to the rest of the specimen. This is dictated by the specific failure mode (LFTF) that involved the whole bonding surface of the adherend.

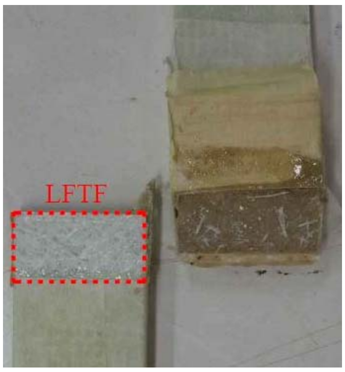

Figure 9: Failure modes of GFRP-GFRP single-lap joints: light-fiber-tear LFTF.

Shear tests on double-lap joints

The test procedures and the parameters evaluated on the double-lap specimen shear tests are the same as for the single-lap ones. Tab. 5 illustrates the average results obtained in terms of ultimate loads, displacements and of the corresponding stiffness (*k*) and ultimate strain and strength.

Adhesive	Nylon reinforcement	F_{max} (N)	τ_{max} (MPa)	γ_{max} (%)	s* (mm)	*k* (N/mm)
EPX1	-	11721 ± 2572	0.33 ± 0.07	14.00 ± 0.75	0.81 ± 0.14	43995 ± 4308
	Middle position	7867 ± 254	0.17 ± 0.03	12.19 ± 0.39	0.49 ± 0.03	55613 ± 350
	on GFRP	8898 ± 225	0.21 ± 0.01	13.79 ± 0.35	0.66 ± 0.18	56406 ± 2506
	on glass	8786 ± 697	0.21 ± 0.03	13.62 ± 1.08	0.63 ± 0.14	57678 ± 7563
	on GFRP and glass	10558 ± 1808	0.25 ± 0.01	15.06 ± 2.80	0.51 ± 0.05	49990 ± 4719
EPX2	-	4513 ± 501	0.20 ± 0.07	6.98 ± 0.79	0.09 ± 0.02	29692 ± 1972
	Middle position	5638 ± 1967	0.14 ± 0.05	6.58 ± 0.87	0.07 ± 0.03	35533 ± 9814
	on GFRP	3851 ± 1283	0.11 ± 0.03	5.97 ± 1.99	0.06 ± 0.02	35458 ± 7085
	on glass	4270 ± 1481	0.11 ± 0.03	6.62 ± 2.30	0.05 ± 0.02	36635 ± 4538
	on GFRP and glass	3469 ± 600	0.08 ± 0.04	4.38 ± 1.41	0.05 ± 0.02	42631 ± 4780
EPX3	-	5459 ±1651	0.24 ± 0.01	9.08 ± 1.49	0.12 ± 0.00	33665 ± 4780
	Middle position	4729 ± 820	0.14 ± 0.04	7.33 ± 1.27	0.07 ± 0.02	36090 ± 5029
	on GFRP	5504 ± 357	0.17 ± 0.02	8.53 ± 0.55	0.09 ± 0.02	34124 ± 2624
	on glass	4353 ± 1899	0.13 ± 0.09	6.75 ± 2.94	0.07 ± 0.05	43835 ± 1794
	on GFRP and glass	4140 ± 2078	0.12 ± 0.06	6.42 ± 3.22	0.07 ± 0.03	37654 ± 3502

* at failure

Table 5: Mechanical properties of GFRP-glass double-lap joints bonded with epoxy adhesives in unreinforced and reinforced configuration.

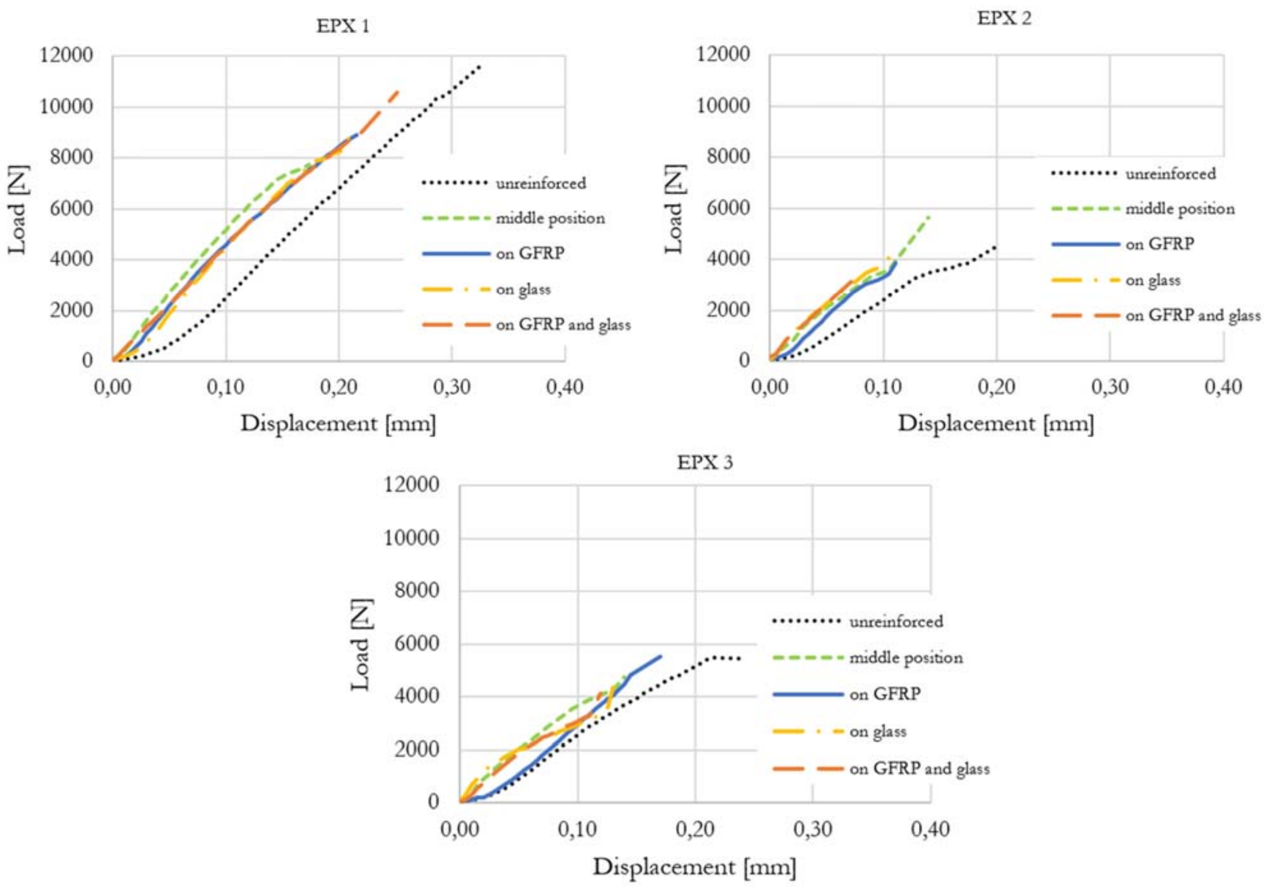

Figure 10: Average load displacement curves of double-lap joints bonded with three different epoxy adhesives in unreinforced and reinforced configurations.

The graphs shown in Fig. 10 compare the load-displacement curves for the adhesives in the reinforced and unreinforced configurations. The curves represent the average graphs of load-displacement curves obtained in the different combinations. The application of the nylon fabric in the adhesive layer causes a decrease in the value of the ultimate strength in almost each application. A reduction in ultimate displacements accompanied by an increase in stiffness of the adhesive joint could be observed. The following is a comparison of the three types of adhesives based on the position of the nylon fabric.
As could be observed, EPX1 adhesive provides the best mechanical performance, in any nylon reinforcement configuration. The reduction in ultimate load for most reinforced joints is due to the interposition of nylon, which has a lower strength than the pure adhesive layer. The nylon-reinforced configuration in the middle position offers the worst mechanical performance, showing a lower ultimate load value of -32.88% compared to the unreinforced configuration. In general, all reinforced configurations exhibit a variable increase in stiffness depending on the position of the reinforcement. In particular, the joint configuration with reinforcement on the glass surface allows to obtain an overall stiffness increase of +31.10%. In the case of EPX2 and EPX3 adhesives, a general decay of the ultimate strength values (up to -24%) is observed, varying according to the combinations tested, except for the configuration with reinforcement in the middle position (EPX2) and on the GFRP surfaces (EPX3) respectively.
Fig. 11 illustrates the stiffness values of the joints as the position of nylon reinforcement changes. The nylon 6 fabric increases the stiffness of the adhesive joint, and the EPX1 adhesive is the best performing in any configuration, especially when the nylon is applied on the glass surface.

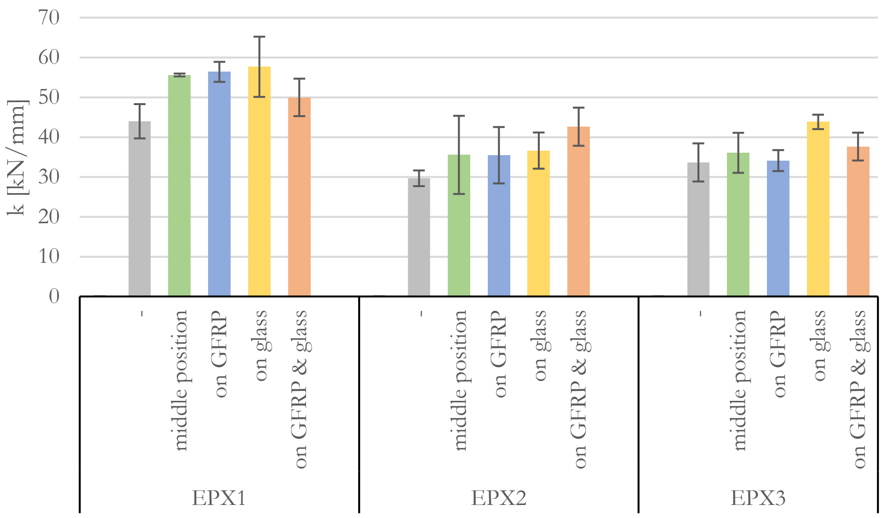

Figure 11: Stiffness distribution of GFRP-glass double-lap joints.

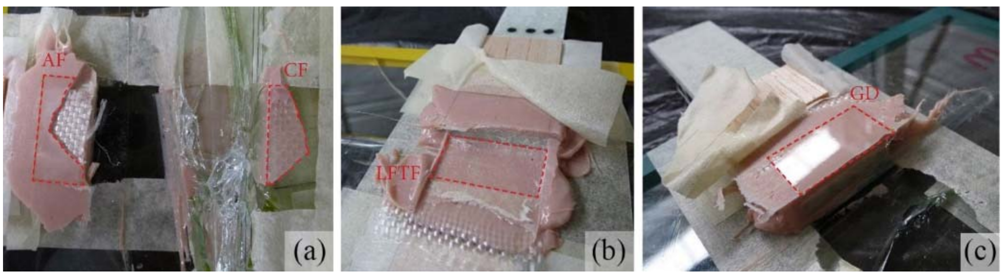

Figure 12: Different types of specimens' failure modes: mixed (a), light fiber tear (b), glass delamination (c) failures

According to ASTM D5573-99 [34], during the test the following failure modes were observed.
The most frequent mode is the MF "Mixed Failure" (Fig. 12a). A combination of adhesive (AF) and cohesive (CF) failure is observed, as shown in Fig. 12a. Part of the adhesive adhering to the GFRP profile and the remaining part adhering to the glass – characterised by the texture of the nylon fabric – could be observed. Fig. 12b illustrates an example of "Light-fiber-tear-failure" LFTF failure: GFRP profile defibration at the adhesive interface could be observed. In this case, the adhesive is perfectly adhering to the glass surface. Fig. 12c shows an example of a failure characterized by the delamination of the glass adherend. A slight defibration of the glass layer in the interface of the adhesive could be observed. In this case the

adhesive is perfectly adhering to the surface of the GFRP. The percentage of failure modes was assessed through a graphical process.

Adhesive	Nylon reinforcement	Failure modes
EPX 1	-	2 MF: (49% AF+ 51% LFTF) 1 MF: (67% AF+ 33% LFTF)
	Middle position	2 MF: (50% AF+ 50% LFTF) 1 MF: (71% AF+ 29% LFTF)
	On GFRP	1 MF: (85% CF+ 15% AF) 1 MF: (95% CF+ 5% LFTF) 1 MF: (89% CF+ 11% LFTF)
	On glass	1 MF: (93% CF+ 7% AF) 2 MF: (95% CF+ 5% AF)
	On GFRP and glass	1 MF: (92 CF+ 8% AF) 2 MF: (93% CF+ 7% AF)
EPX 2	-	3 AF
	Middle position	1 LFTF 1 MF: (80% LFTF+ 20% AF) 1 MF: (60% LFTF+ 40% AF)
	On GFRP	1 MF: (30% CF+ 70% AF) 2 LFTF
	On glass	3 LFTF
	On GFRP and glass	1 GD 1 LFTF 1 MF: (50% LFTF + 30% AF + 20% CF)
EPX 3	-	2 CF 1 MF: (50% AF + 50% LFTF)
	Middle position	1 GD 1 LFTF 1 MF: (GD + CF)
	On GFRP	1 MF: (70% LFTF + 30% AF) 1 MF: (30% LFTF + 70% AF) 1 GD
	On glass	1 MF: (50% AF + 40% CF + 10% LFTF) 1 MF: (83% CF + 17% AF) 1 MF: (52% AF + 48% CF)
	On GFRP and glass	2 GD 1 MF: (80% AF + 20% CF)

Table 6. Summary of failure modes observed in double-lap adhesive joint.

Adhesive	Configurations	F_{max} (N)	Displacement* (mm)	k (N/mm)
EPX1	Steel plate	18545 ± 2592	9.72 ± 4.58	2725 ± 142.96
	Nylon and steel plate	17527 ± 900	7.63 ± 0.03	2506 ± 139.38
EPXRN	Nylon	18997 ± 1288	12.88 ± 3.66	2210 ± 32.19
	Steel plate	16589 ± 2235	8.25 ± 0.26	2796 ± 111
	Nylon and steel plate	16509 ± 1461	7.67 ± 0.68	3140 ± 113.72
-	unreinforced	16118 ± 1580	8.82 ± 0.40	2183 ± 45.60

* at failure

Table 7. Mechanical properties of GFRP squared specimens, with and without the steel and nylon reinforcement.

Tab. 6 summarizes the failure modes occurred according to the adhesive used. It could be observed that for the EPX3 adhesive there is a mixed failure in 58% of cases, LFTF in 8% and glass delamination for 30% of specimens. For the EPX2 adhesive, there is a 33% mixed failure, 58% LFTF type and the remaining 8% failure with glass delamination. All specimens made with EPX1 adhesive shown mixed failure.

Three points bending tests

Tab. 7 shows the average values of the GFRP squared tubular profiles subjected to the three points bending tests relatively to the maximum load (N), to the maximum displacement in the middle (mm) and to the stiffness (N/mm) as the position of the reinforcement changes.

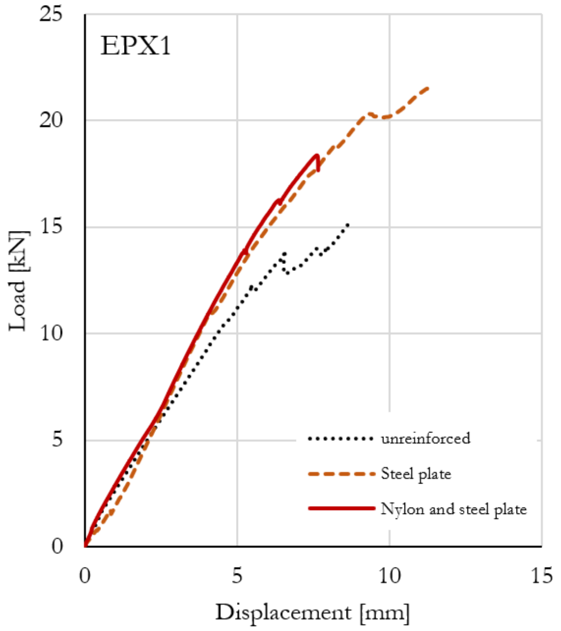

Figure 13: Average load displacement curves of GFRP tubular profiles in unreinforced and reinforced configurations, bonded with EPX1 adhesive.

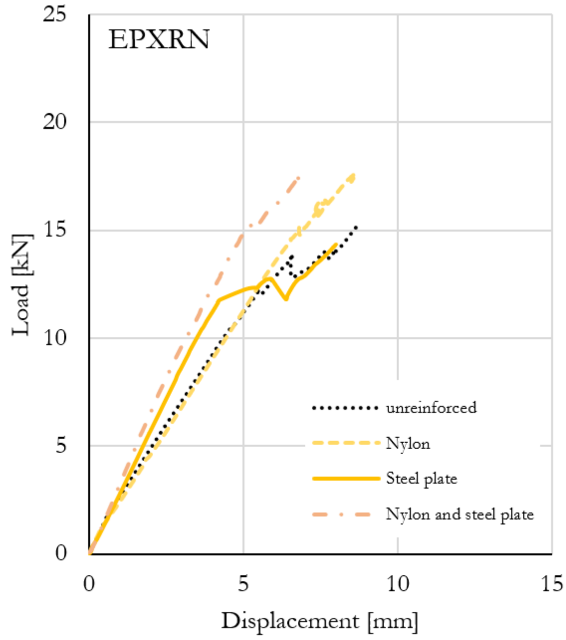

Figure 14: Average displacement curves of GFRP tubular profiles in unreinforced and reinforced configurations, bonded with EPXRN adhesive.

Since the lower flange is the most stressed part of the profile, it was decided to test experimentally only the configurations with the reinforcement applied on the outer surface of the flange. The adhesives used are the EPXRN resin and the EPX1 structural adhesive, selected from the previous tests. The mechanical performance of unreinforced pultruded profiles was improved by reinforcements in all the configurations tested. Experimental stiffness k was in any case superior to the stiffness of the pultruded GFRP samples without reinforcement (Figs. 13-14), up to a maximum of 43% in the nylon and steel reinforcement configuration. Bondings with the EPXRN resin exhibited the best mechanical performance, while reinforcements applied with EPX1 provided an increase in stiffness of up to 15% if compared to the unreinforced configuration. Finally, it was observed that the beams reinforced with nylon 6 and those reinforced with steel plates observed an increase in stiffness of 29% and 26% respectively if compared to the unreinforced beams.

Failure modes

Fig. 15 illustrates the failure mode of the non-reinforced GFRP specimen. In the middle section of the beam, the concentrated applied load causes a localized failure on the corners of the section. A lower value of the deflection at failure on the specimens with both reinforcements was observed.

Figure 15: Failure mode of GFRP specimen.

In the specimens reinforced by the EPX1 adhesive, the materials applied as reinforcement showed no delamination (ND failure); failure was due to a localized failure on the corners of the section, as for unreinforced specimens. The beams reinforced with EPXRN resin (Fig. 16) showed failure at the interface between resin and steel plate, classifiable as "adhesive" failure (AF) according to CNR DT 200/2004. The steel plates constituted the surface in which detachment was more easily obtained by delamination of the reinforcement of the beams due to their smooth surface. The adhesive failure mode (AF) between the resin and the steel plate occurred earlier than the cohesive failure of the resin, therefore the internal cohesion of the nylon 6 fabric was higher than the adhesion to the steel reinforcement.

Figure 16: Failure mode of GFRP specimen reinforced with epoxy resin EPXRN and steel plate.

Conclusions

In this study, an experimental campaign to analyze the effectiveness of the application of nylon 6 fabric in adhesive joints in building components is proposed.

Mechanical tests were performed on three types of specimen:

- Shear tests on GFRP-GFRP single-lap specimens, adhesive joint both unreinforced and reinforced with nylon 6 fabric were tested;
- Shear tests on GFRP-glass double-lap specimens, in which nylon was interposed using three types of epoxy adhesives and tested in shear with optical measurement;
- GFRP squared tubular profiles in three-point bending tests, both in the unreinforced configuration and with two different epoxy adhesives according to different reinforcement configurations.

The main outcomes are:

i. Shear tests shown that applying the nylon 6 fabric in the adhesive layer improves the mechanical performance in terms of stiffness, with different failure modes depending on the material used.
ii. Shear tests on single-lap specimens showed that nylon 6 fabric increased the stiffness of adhesive joints while the ultimate strength was reduced, and displacements were more contained. Load-displacement curves were simplified into bilinear curves since the joint did not show linear behavior.
iii. Shear tests on double-lap joints showed that EPX1 adhesive exhibited the best mechanical behaviour, especially when the nylon was applied on the glass surface, as it achieved better adhesion to the substrate. Contained deformations, due to the presence of the nylon fabric, were observed.
iv. Bending tests performed on tubular squared GFRP beams showed an increase in stiffness with the application of the nylon fabric in the adhesive layer with the steel plate reinforcement, especially in the case of the EPXRN resin. For this configuration, at failure, the detachment of the steel plate was observed. In this case an additional layer of resin could be applied to increase the ultimate strength, or a metal surface corrugation treatment could be made improving the adhesion between the steel plate and the adhesive.

Previous works [18,19,34], show the effectiveness of the adhesive bond. Due to the proven structural cooperation between glass and substrate element, stiffness increases in the resulting structure are achieved [19], and hybrid structures with high ductility could be obtained [18,34].

The results listed in this paper show the effects of the nylon fabric reinforcement system on the mechanical behaviour of adhesive joints.

In general, in the various applications tested, the effect of nylon fabric reinforcement results in a reduction of the ultimate load and an increase in the overall stiffness of the joint. A further advantage of this technology is the improved adhesion between GFRP and glass substrates. In fact, an increase in the percentages of LFTF and CF failure modes is observed, in contrast to the higher percentages of adhesive (AF) failure modes in the case of unreinforced joints. Therefore, this type of reinforcement proves to be appropriate for the application on structural elements of GFRP curtain walls since - with the

same load - an increase in stiffness is obtained which allows the reduction of the maximum deformations (e.g. resistance to wind loads for windows and doors, classification according to the UNI EN 12211 test method [25]).
However, the reinforcement system studied implies a complication of the mass production process, with a possible increase in costs, for example in terms of time and types of production controls. Once the mechanical effectiveness of the reinforcement for the uses considered has been verified, a scale test will follow on the possible production processes and on the economic character of the technology illustrated.

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