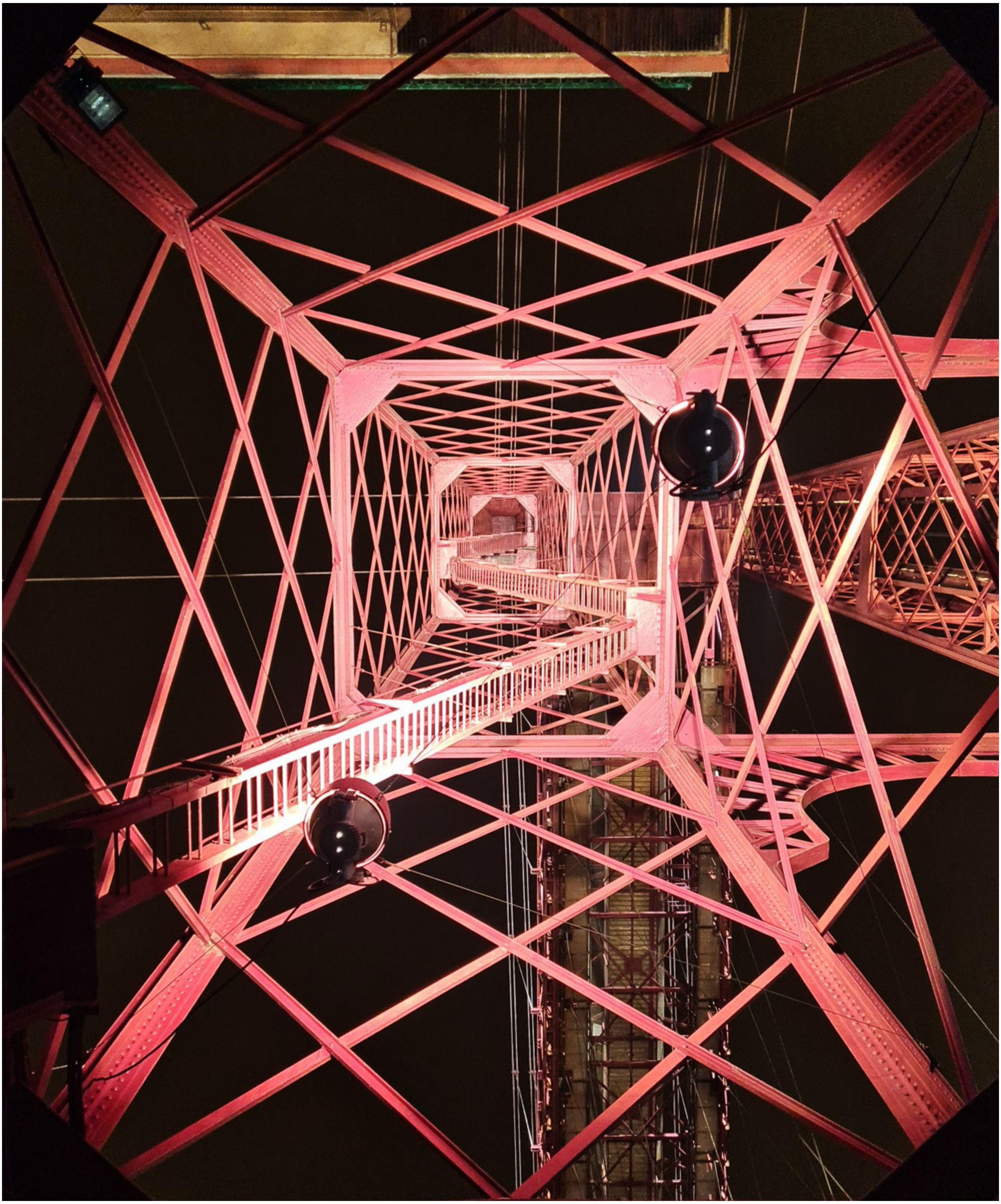

TEMA

Technologies Engineering Materials Architecture

Journal Director: R. Gulli

e-ISSN 2421-4574

DOI: 10.30682/tema0802

Vol. 8, No. 2 (2022)

Issue edited by Editor in Chief: R. Gulli

Cover illustration: "Puente Colgante" or Vizcaya Bridge in Portugalete-Getxo (Biscay, Spain) by Alberto Palacio. © Riccardo Gulli, 2022

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
ISBN online 979-12-5477-184-6
DOI: 10.30682/tema0802
Vol. 8, No. 2 (2022)
Year 2022 (Issues per year: 2)

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TEMA: Technologies Engineering Materials Architecture
Vol. 8, No. 2 (2022)
e-ISSN 2421-4574

APPLICATION OF ADHESIVE TECHNOLOGY TO A NEW TYPE OF GLAZED PANEL FOR CURTAIN WALLS WITH AN INTEGRATED FRAME

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TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 8, No. 2 - (2022)

DOI: 10.30682/tema0802c

This contribution has been peer-reviewed.

Abstract

The adhesive technology offers several advantages over traditional joints, allowing the assembly of construction elements with a reduced number of components. The use of large glazed surfaces is a distinctive feature of modern architecture and is reflected in the curtain walls. In traditional applications, glazed panels simply transfer the stress to the substructure (frame), not assuming a structural role. This article reports the results of an experimental campaign on a new type of wooden panels for windows and curtain walls (patent application No. 1020000023128 and European patent 3071775) which provides for the structural collaboration between the frame and glass panels using adhesives. This solution (glazed panels adhesively bonded to the wooden frame) adequately responds to the performance requirements of the highest class of resistance to wind load for windows (C5 – UNI EN 12207), limiting the maximum displacement within 1 mm (maximum deflection of the order of 1/1500).

Keywords

Timber-glass adhesive joint, Flexural tests, Adhesive bonding, Hybrid adhesive joint.

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Nomenclature

A_t	Application temperature
E_t	Young Modulus in tension
F	Applied load
k	Stiffness
s	Displacement
S_t	Service temperature
W_t	Working time
α	Thermal coefficient of expansion
ε_t	Tensile strain
σ_t	Tensile strength
σ_c	Compressive strength
τ	Shear strength

1. INTRODUCTION

The latest regulatory developments have influenced the design of building components with increasingly demanding performance requirements for both materials and components. The current trend is the search for slender structures with high mechanical, acoustic, and energy performance while the present market demand is oriented towards large glass surfaces and transparent casings with low environmental impact [1, 2]. In these types of solutions, the glazed surfaces are usually carried by a metal frame (i.e., stainless steel or aluminum) to which the glass panels transfer the load.

Design and calculation need to take into account the interaction of the glass panels with the substructure. The connections are usually made with mechanical or adhesive splices. In the field of curtain walls, solutions involving the use of silicone adhesives are offered for example by Dow Corning. However, these are improperly defined as “structural” as the adhesives used to create a bond that cannot be entrusted with the mechanical collaboration between the glass paneling and the frame. This adhesive bond solution does not guarantee a satisfactory stiffness of the glass-frame junction and, for this reason, the glass panels require supports. Furthermore, the difference in thermal expansion coefficients between the glass and the substrates requires the use of a flexible structural adhesive, capable of effectively absorbing the differential deformations between the components. The impossibility of obtaining structural collaboration between glass and substrate with silicone adhesives leads to the use of considerable sections for the substructure elements.

The failure phenomena of silicone adhesives in building facades have been extensively studied by Chew [3] with in situ diagnostic studies comparing silicone to other polyurethane adhesives. The results highlight the lower adhesion of silicone to substrates compared to the other adhesives tested.

A couple of examples of silicone adhesive joints applied to curtain walls are the Dow Corning warehouse in Feluy, Belgium (Fig. 1a) and the Hermès flagship store in Amsterdam (Fig. 1b). In the first case, the stainless-steel connectors of the curtain wall are joined to the glazed panels by means of silicone; in the second building instead, a thin transparent adhesive was used, in which glass blocks are glued together in imitation of traditional masonry [4].

The results of the research on polymeric materials have highlighted the numerous advantages offered by the adhesive technology compared to the traditional joining methodologies (e.g., riveting, bolting, welding) [5, 6]. As a matter of fact, adhesive joint structures have high ultimate strengths and uniform distribution of stresses, with reduced peaks [7]. Thus, this technology has proven to be valid in hybrid joints for composite materials [8] (e.g., GFRP) which are sensitive to concentrated loads. In the field of civil engineering, adhesive technology is used in the construction of hybrid steel and glass structures [9, 10], structures in composite material [13], and facade cladding [11, 12]. Silvestru et al. [14] proposed new solutions for acrylic adhesive joints between glass and metal for curtain walls. The experimental in-plane and out-of-plane shear tests on full-scale specimens have shown that such structures have a high load-bearing capacity. Subsequent finite element analyses validated the experimental results.

(a) (b)

Fig. 1. *Real cases of application of structural adhesives for building facades.*

Richter et al. [15] studied the use of hyper-elastic adhesives to assemble facade panels by means of FE analysis on steel-glass joints. Laboratory tests were also performed on scaled components under different load conditions. Further studies [16–18] investigated the application of adhesive technology for curtain walls; however, bonding was not extended to all the perimeter surfaces of the glazed panels. In the works by Feldmann et al. [19] and Abeln et al. [20] experimental tests were carried out to investigate the ductility and strength of hybrid steel and glass adhesives joints. Bues et al. [21] investigated the bearing capacity of adhesive joints with different geometries, load directions, and temperatures by means of experimental campaigns on silicone adhesives for adhesive joints.

The use of adhesive wood-glass joints results in structures with high mechanical performance and, thanks to a major reduction in the frame size, great aesthetic value [22]. Piculin et al. [23] studied solutions for composite wood and glass panels joined with epoxy adhesives on scale samples obtaining encouraging results. Blyberg et al. [24–26] investigated the mechanical performance of silicone, acrylic, and polyurethane adhesives in applications on wood-glass joints with tensile and shear tests. Further experimental studies carried out by Kozlowski [27] on wood-glass structural elements assembled by means of an adhesive joint highlighted the improved mechanical performance offered by epoxy adhesives compared to traditional silicone adhesives.

Fig. 2. *Patent application No. 1020000023128, prototype.*

This study shows the results of an experimental campaign aimed at investigating the benefits of adhesive technology to the mechanical performance of new types of frames for doors, windows, and curtain walls. The performance of mahogany wood frames adhesively bonded to glass panels with float glass reinforcements is investigated in terms of global displacements, stiffness, and residual displacement. The used frame technology, shown in Fig. 2, refers to the patent application 1020000023128 «Frame for windows, doors and external perimeter panels made with profiles joined with structural adhesives – double glazing with spacer joined with structural adhesives (inventor: P. Munafò)».

2. MATERIALS AND METHODS

This section describes the mechanical characteristics of the materials and the test methodologies used in the experimental campaign.

2.1. ADHERENDS

Three different adherends were used: float glass panels (supplied by Vetreria Incicco, Italy), GFRP flat profiles (Fibrolux, Germany), and mahogany profiles (Dorica Legnami, Italy). The properties of the materials, provided by the manufacturers, are reported in Tables 1 and 2.

Adherends	Sapelli Mahogany
Category	Hardwood
Fresh density (kg/m^3)	780
Density after maturation (kg/m^3)	620
Histological structure	Fine texture
Fibration	Interwoven
Retire	Moderate
σ_c* (MPa)	55
Use	Structural

*along the fibres

Tab. 1. *Timber mechanical properties reported by manufacturers.*

GLASS*		
α (°C^{-1})	E_t (GPa)	σ_t (MPa)
9×10^{-6}	75	40

*according to CNR-DT 210/2013 [19]

Tab. 2. *Glass mechanical properties.*

2.2. ADHESIVES

A two-component epoxy structural adhesive (2K) EPX was used throughout the experimental campaign. This adhesive was chosen on the basis of the results obtained in previous experiments conducted by the same research group [28–32]. Tab. 3 shows the mechanical characteristics of the adhesive specified by the manufacturer in the technical data sheet.

Adhesive	EPX
Chemical base	Two-part epoxy
Viscosity	Thixotropic
W_t (min)	16
A_t (°C)	15÷25
T_g (°C)	66.87
S_t (°C)	-40÷80
τ*(MPa)	29.40*
E_t (MPa)	1500
ε_t **(%)	-
Use	Semi-Structural

* On aluminium-steel adherends
**At failure.

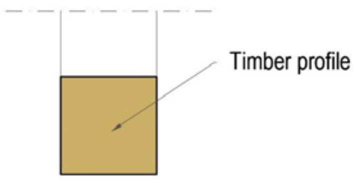
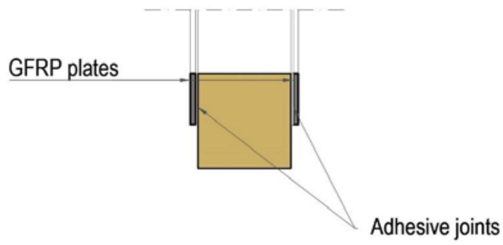
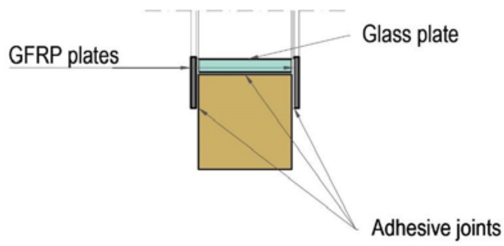
Tab. 3. *Mechanical characteristics of the adhesive reported by manufacturer.*

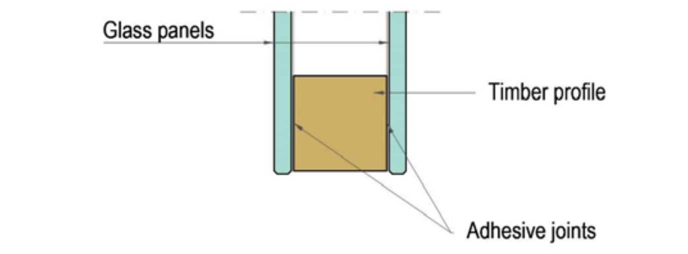
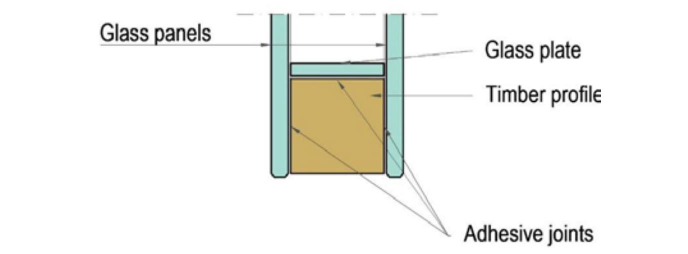
2.3. SPECIMENS: WINDOW AND DOOR FRAMES

Described materials have been used to assemble panels with the dimensions of 0.40 m x 1.24 m^2. In configurations (iv) and (v) panels are reinforced with float glass panels. Table 4 summarizes all tested configurations.

The cross section of the wooden frames has envelope dimensions of 47 x 45 mm^2. The external glazed panels to which the frame is adhesively bonded have a thickness of 6 mm. The GFRP and internal float glass reinforcement plates have sections of 2.40 x 24 mm^2 and 30 x 6 mm^2, respectively.

Glazed panels were bonded under laboratory conditions (21°C and RH 50%). All adhesive regions have a thickness of 1.10 mm, obtained through the use of spacers. Before the gluing phase, all the surfaces of the adhesives were manually cleaned with denatured isopropyl alcohol. The maturation of the frames lasted 28 days, in laboratory conditions (21 ± 2°C and RH 50 ± 8%), according to the specifications provided by the manufacturer of the adhesive used.

Acronym	Description	Cross-section
URM-M	Unreinforced mahogany wood frame	
RM-MG	Mahogany wood frame laterally reinforced with flat GFRP profiles	
RM-MGV	Mahogany wood frame reinforced with flat GFRP profiles laterally and glass profile in intermediate position (Patent Application n. 102020000023128)	

RM-MVV	Mahogany wood frame with float glass panels adhesively bonded to the wooden profile (European Patent n. 3071775)	
RM-M2V	Mahogany wood frame with float glass panels adhesively bonded to the wooden profile, reinforced with glass profile in intermediate position (European Patent 3071775 Patent Application n. 102020000023128)	

Tab. 4. *Tested panels.*

2.4. TEST SETUP

The experimental campaign consists of bending tests on frames for doors, windows, and curtain walls, to verify the structural collaboration between the components bonded together by means of an adhesive joint. Figure 3 shows the test setup.

Each load test was carried out by manually adding up the load with steps of 20 and 10 kgf, distributing the load on two points aligned on the center line, and simultaneously measuring the derived deformation. The purpose of this experimental setup is to statically simulate the action of the wind on the window frame. The applied load was gradually increased until reaching the limit value of the deformation for class C5 windows (i.e., maximum deformations contained within 1/200 of the height of the frame, equal to 6.20 mm), according to the UNI EN 12207 [33]. The maximum applied load is 1.47 kN, or a lower value when it led to the achievement of the maximum deflection.

Displacements were recorded at seven measurement points using vertical transducers (24 bit MAE LVDTs) located at the intrados of the profiles. The vertical transducers are analog potentiometers (model PY2C-50P) supplied by MAE (uncertainty of the instrument equal to ± 0.01 mm).

For each configuration, three specimens were tested, each of them subjected to three loading-unloading cycles, to reduce the influence of the rheological properties of the material and the uncertainty of the measurements on the experimental results.

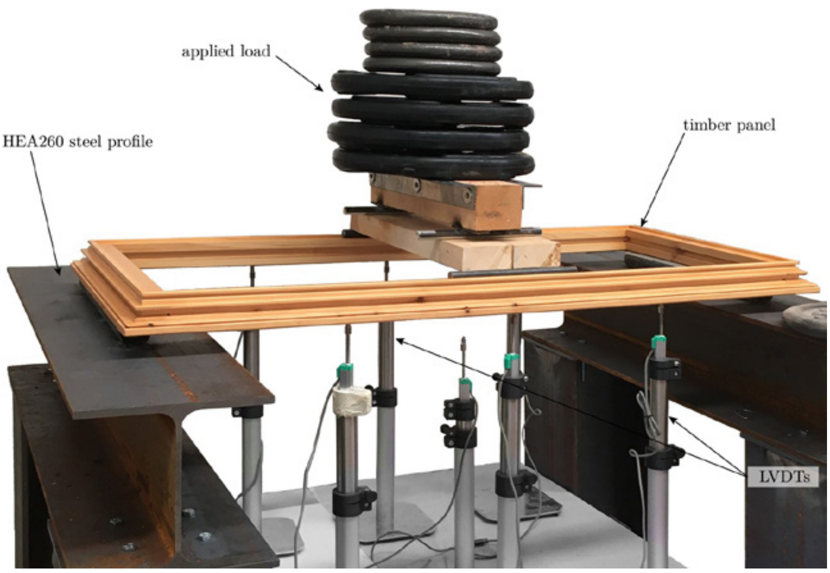


Fig. 3. *Test setup.*

3. RESULTS AND DISCUSSION

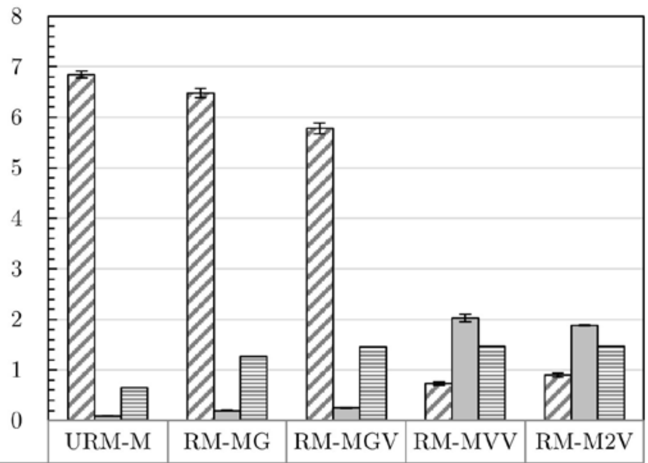
This section presents the results of the experimental campaign. Average values of maximum load, measured displacements, global stiffnesses, and maximum residual displacements are analyzed (Fig. 4 and Tab. 5).

The maximum deformations are registered for non-reinforced frames (6.84 mm) at low values of the load (0.66 kN). The addition of GFRP reinforcements adhesively bonded to the frames (RM-MG) allows for almost doubling the stiffness compared to non-reinforced ones. A further increase in stiffness is registered for frames reinforced with flat GFRP profiles and glass (RM-MGV), showing deformations compatible with those provided for by class C5 (≤ L/200 = 6.20 mm) when subjected to the maximum prefixed load (1.47 kN). Both the configurations with external glazed panels adhesively bonded to the mahogany frame (RM-MVV and RM-M2V) show the best performance in terms of stiffness (around 2 kN/mm) and maximum displacements (within 1 mm).

The maximum residual deformations (sres) are observed for GFRP reinforced frames (configurations RM-MG and RM-MGV), which also show the largest standard deviation. Configurations with external glass panels (RM-MVV and RM-M2V) have a residual displacement of an order of magnitude smaller, but the standard deviation is also in this case comparable with the deformation.

Figure 5 shows the response of the different configurations in terms of load-deformation. Each curve in diagrams a) to e) corresponds to a loading or unloading stage: it can be noted that the residual deformation remains constant after each unloading, not adding up to that of the previous cycle. Diagram f), instead, compares the first-load curve of each configuration.

All loads used were compatible with the elastic behavior of the materials involved in the specific test, so as



	URM-M	RM-MG	RM-MGV	RM-MVV	RM-M2V
Displacement (mm)	6.84	6.48	5.78	0.73	0.90
k (kN/mm)	0.09	0.20	0.25	2.03	1.88
Max Load (kN)	0.65	1.27	1.47	1.47	1.47

Fig. 4. *Mechanical properties of frame specimens.*

Frame	Configuration	F_{max} (kN)	s_{max} (mm)	f_{max} (s_{max}/L)	k (kN/mm)	s_{res} (mm)
Mahogany	URM-M	0.66	6.84 ±0.14	1/181	0.10 ± 0.00	0.12 ± 0.02
	RM-MG	1.30	6.48 ±0.18	1/191	0.20 ± 0.01	0.27 ± 0.24
	RM-MGV	1.47	5.78 ±0.21	1/215	0.26 ±0.01	0.28 ± 0.13
	RM-MVV	1.47	0.73 ±0.06	1/1700	2.07 ± 0.16	0.03 ± 0.02
	RM-M2V	1.47	0.79 ±0.08	1/1570	1.91 ± 0.20	0.03 ± 0.04

Tab. 5. *Mechanical parameters measured with standard deviations.* δ_{max} (L/200) = 6.20 mm.

no crisis modes or significant plastic deformations were found. However, the RM-MGV configuration recorded the failure of the glass reinforcement (Fig. 6), which was due to the incongruity between the deformations of the frame and those of the glass reinforcements. Figure 6a shows the triggering of the crisis in the glass reinforcement plate and Figure 6b its propagation in the material due to the subsequent load increase.

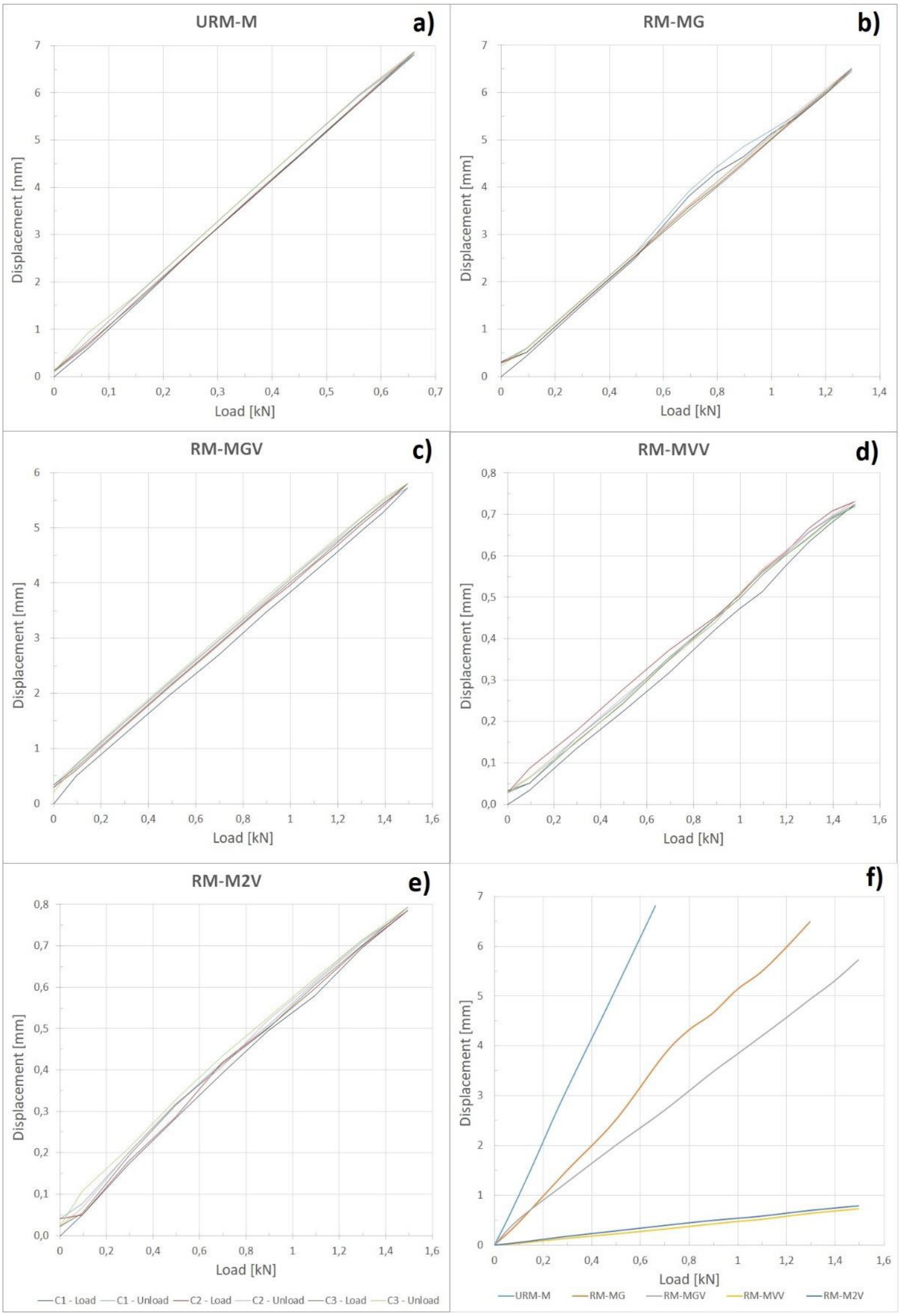


Fig. 5. *Each curve (blue: first load, light blue: first unload, red: second load, pink: second unload, dark green: last load, light green: last unload) in graphs (a) to (e) represents the displacement measured in each load or unload cycle averaged on the three samples investigated. In graph (f) each curve represents the first load cycle of a different typology of the frame.*

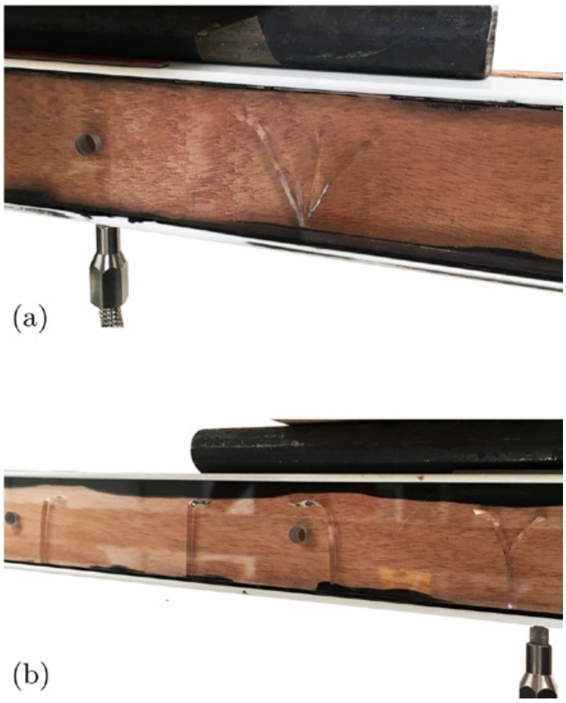


Fig. 6. *Failures in the glass reinforcement layer (RM-MGV): failure initiation (a); crack propagation (b).*

The results obtained for the unreinforced configuration reflect the characteristic stiffness of the material. The introduction of the adhesive joint between the frame and the glass panels and between the frame and the reinforcements (GFRP and internal glass plates) allows to obtain an improved structural collaboration between the components, leading to a structure with increased stiffness and maximum deformation within one millimetre.

4. CONCLUSIONS

This work presents the results of an experimental campaign carried out on an innovative type of frame for windows, doors, and curtain walls, in which the mahogany structure is adhesively bonded to the glazed panels using epoxy adhesive selected on the basis of previous research work. Several configurations were tested, including some of them with internal glass plates reinforcement. The results are analyzed in terms of maximum displacements, residual displacement, and global stiffness of the resulting element.

In light of the results obtained, the following conclusions can be drawn:

- the adhesive joints are able to realize an effective structural collaboration between the components adhesively joined together;
- the glass reinforcements plates cause a slight decrease in the maximum displacements, compared to the analogous non-reinforced configuration. In the case of GFRP reinforced frames, they also permit an increase in the ultimate load of 11.5%;
- the combination of the examined reinforcing techniques, applied on frames adhesively bonded to the glazed panels, leads to more rigid structures, showing maximum deformation within 1 mm and maximum deflections (f) within the C5 threshold (Tab. 4).

Results are promising about the application of adhesive technology in the civil engineering sector, and in particular for windows, doors, and curtain walls.

The registered increase in stiffness and decrease in the maximum displacement (especially for configurations RM-MVV and RM-M2V) envisages the possibility of using large glazing panels (e.g., 2.7 m x 3 m) with reduced size of the frame (30 mm x 30 mm).

Authors contribution

Experiments, writing, conceptualization and revision, F.M.; writing, revision, R.A.; supervision, conceptualization, P.M.

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