International Journal of Adhesion & Adhesives 105 (2021) 102788

Contents lists available at ScienceDirect

International Journal of Adhesion and Adhesives

journal homepage: http://www.elsevier.com/locate/ijadhadh

Temperature effects on failure mode of double lap glass-aluminum and glass-GFRP joints with epoxy and acrylic adhesive

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ARTICLE INFO

Keywords:
Mechanical properties of adhesives
GFRP pultruded Profiles
Aluminum
Double-lap joints
Hybrid bonded joints

ABSTRACT

In this experimental study, a series of mechanical tests were conducted on double-lap joint specimens, where glass sheets were adhesively bonded on two different supports, namely aluminum and glass fiber reinforced polymer (GFRP). Five different types of adhesives (three epoxy and two acrylic) were compared and three temperature conditions (room temperature, work temperature and maximum service temperature) were investigated. The main aim is to verify the applicability of this type of junction on civil applications, such as windows, glass façades, and so on.

The first part of this study describes the results of tensile tests conducted in order to verify the compatibility of the bonding system at room temperature; the second part illustrates the degradation of the adhesive bonding due to high temperatures; in fact, if used in civil applications, these junctions are generally exposed to severe temperatures that could reach the glass transition temperature of the used adhesive, this leads to the necessity to verify the correct functionality of the adhesive joint.

The results evidenced that the mechanical performance of adhesive junctions is considerably reduced as the temperature increases. This phenomenon is more evident in acrylic adhesives rather than epoxy ones. The epoxy adhesives in all tests exhibited the highest load carrying, while the acrylic ones showed the highest joint elongations.

Different failure modes, classified as "Adhesive Failure", "Cohesive Failure", "Light-Fiber-Tear Failure" or "Mixed Failure", were observed at room temperature while, at high temperatures, only "adhesive failure" was observed. The study demonstrates that high temperatures have a remarkable impact on the mechanical properties of adhesive junctions. Such effect should be suitably taken into account in the design and verification phase of components.

The research results can be appropriately used in practical applications.

1. Introduction

During last decades, in the framework of civil and mechanical engineering, new building materials, such as Glass Fiber-Reinforced Polymer (GFRP), structural adhesives [1], and structural glass, aroused a great interest. For example, GFRP can be used in alternative to conventional materials: Keller [2] showed applications in bridges and buildings, Godat et al. [3] proposed FRP elements to be used in electricity transmission towers [3], Appelfeld et al. developed a GFRP window frame [4], and so on. Structural glass, widely used for wall façade system, has been utilized in different applications: glass floor, as showed by Alderucci et al. [5], glass columns and beams, as studied by Foraboschi et al. [6]. GFRP pultruded profiles present several advantages if compared to traditional materials, for example high specific yield strength, light weight, low electrical and thermal conductivity, non-corrodibility, rapid installation time and low life-cycle costs [3,7]. At the same time, different authors investigated several factors which make impossible the use of GFRP to many applications: Turvey [8] studied the effects of their orthotropic nature; de Castro and Keller [9]

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https://doi.org/10.1016/j.ijadhadh.2020.102788

Available online 10 December 2020

Nomenclature

α	Thermal coefficient of expansion	k	Stiffness
ACR1	First acrylic adhesive	S_t	Service temperature
ACR2	Second acrylic adhesive	W_t	Working time at 22 °C
A_t	Application temperature	ε	Tensile ultimate strain
EPX1	First epoxy adhesive	σ	Tensile ultimate stress
EPX2	Second epoxy adhesive	σ_{ys}	Tensile yield stress
EPX3	Third epoxy adhesive	τ	Shear strength
E	Young modulus in tension	T_g	Glass transition temperature

highlighted the brittleness in bolted connections [9]; Kim and Lee [10] evidenced the low elastic modulus if compared to steel (up to ten times lower). Borowicz and Bank [11] showed that all these aspects get worse especially when concentrated bearing loads are applied. Furthermore, the extreme sensitivity of GFRP to fire remains a problem of great complexity. With regard to structural glass joined with other materials, its intrinsic brittle behavior makes the classic bolted connection not suitable, so the adhesive conjunction should be preferred. In this framework, several authors, such as Machalická and Eliášová [12], demonstrated how the new capabilities of adhesives allowed the development of hybrid glass-steel structures. Stazi et al. [1], through an extended experimental campaign, demonstrated the effectiveness of an adhesive junction between two GFRP profiles, while Giampaoli et al. [13] showed the compatibility between GFRP profiles and steel. Instead, there are few studies about the compatibility of glass-aluminum and glass-GFRP adhesive joints.

However, even if adhesive bonding is suitable to be used for bonding dissimilar materials, Marquesa et al. [14] pointed out that it is necessary to consider that these materials may have very different coefficients of thermal expansion. This implies that in the design phase of the adhesive joint not only the mechanical acting forces should be taken into account, but also the elements to which it is exposed during service. Mechanical stress, elevated temperatures, and high relative humidity can be a fatal combination for certain adhesives if all occur at the same time. In particular it is important to consider thermal effects because these generally lead to a joint strength reduction, as discussed by Viana et al. [15], even though da Silva et al. [16] highlighted that in some cases the opposite happens.

In this paper, the mechanical properties of two hybrid adhesive joints, i.e. glass-aluminum and glass-GFRP, are studied. The first aim of the study is verifying the compatibility of the bonding system at room temperature, through tensile tests on double-lap specimens with different adhesives (three epoxy and two acrylic), in order to select the best product. Then, having in mind the possibility to use this joining in a particular window's frame, since different materials with different thermal expansion coefficients are tested, the second aim of the paper is quantifying the decay of the mechanical performances as the temperature rises. To this purpose, further tests were conducted at various temperature conditions, i.e. work temperature and maximum service temperature.

An analysis on the fracture modes was also done, in particular, different failure modes, classified as "Adhesive Failure" (AF), "Cohesive Failure" (CF), "Light-Fiber-Tear Failure" (LFTF) and "Mixed Failure" (MF), were observed at room temperature. At high temperatures, instead, all failures observed during the tests were classified as "adhesive failure". The paper demonstrates that high temperatures affect considerably the mechanical properties of hybrid adhesives junctions, the experiments and the outcomes to justify this statement are thoroughly presented and discussed in the following sections.

Table 1
Glass, Aluminum, GFRP mechanical properties according to manufacturer's data sheet.

GLASS			ALUMINUM PROFILES[a]					GFRP PROFILES[b]				
$\alpha(^{\circ}C^{-1})$	E(GPa)	σ(MPa)	$\alpha(^{\circ}C^{-1})$	E(GPa)	σ_{ys}(MPa)	σ(MPa)	ε(%)	$\alpha(^{\circ}C^{-1})$	E(GPa)	σ(MPa)	ε(%)	Tg[c] (°C)
9×10^{-6}	75	40	23.2×10^{-6}	69	250	295	8	11×10^{-6}	26	400	1.5	123

[a] According to UNI EN 755–2:2016 [17].
[b] According to ASTM D638:2014 [18].
[c] Of the vinyl ester matrix.

Table 2
Technical and mechanical characteristics of the adhesives reported by manufacturers.

Adhesives	*EPX1*	*EPX2*	*EPX3*	*ACR1*	*ACR2*
Chemical base	Two-part epoxy adhesive	Two-part epoxy adhesive	Two-part epoxy adhesive	Acrilyc	Acrilyc
Consistency	Controlled flow	Pasty	Pasty	Tape	Tape
W_t (min)	90–300	16	17	/	/
$A_t(^{\circ}C)$	15–25	15–25	15–25	21–38	20–40
$S_t(^{\circ}C)$	−50 + 120	−40 + 80	−40 + 84	−35 + 90	−35 + 110
$T_g(^{\circ}C)$	61.07	66.87	/	69.37	69.37
$\alpha(^{\circ}C^{-1})$	1×10^{-4}	/	/	18×10^{-5}	18×10^{-5}
Surface treatments	Sand	Sand and degrease	Sand and degrease	Sand and degrease	Sand and degrease
τ^* (MPa)	33.50	29.40	36.60	0.48	0.55
σ(MPa)	/	/	/	0.59	0.97
E (MPa)	3000	1800	2600	0.9	1.8
ε(%)	3	/	/	/	/
Use	Structural	Semi-structural	Semi-structural	Structural	Structural

*On aluminum-steel adherents.

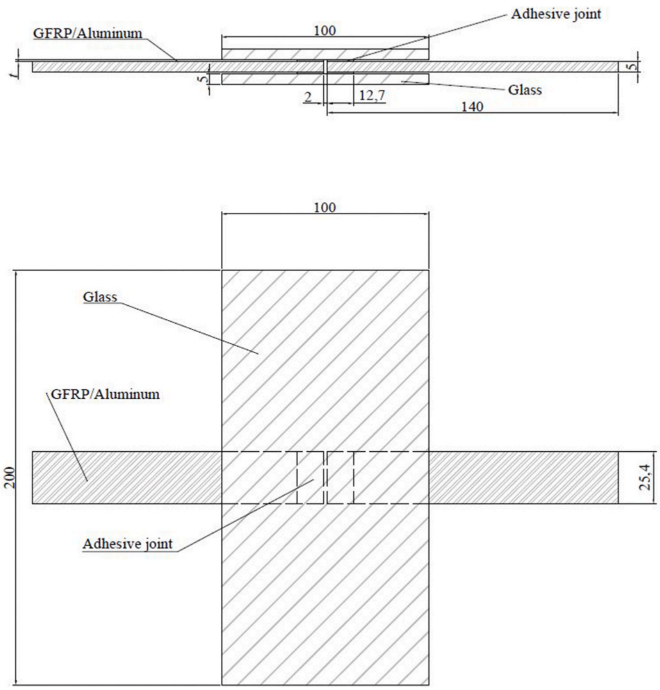

Fig. 1. Double-lap specimens geometry (mm).

2. Materials and methods

In order to verify the compatibility and the temperature effect of glass-aluminum/glass-GFRP junctions, tensile tests on adhesively bonded double lap joints were conducted. In this section, the used materials and the experimental conditions are presented.

2.1. Materials properties

2.1.1. Adherents

Three different materials were used in this work, supplied by local producers: float glass, supplied by VETRO Z (Ancona, Italy), aluminum, supplied by METAG (Osimo, Italy), and GFRP, supplied by PCR srl (Bernareggio, Italy). The mechanical properties of the three materials, provided by the manufacturers, are reported in Table 1.

In this experimental work GFRP profiles made of pultruded E-glass fiber reinforced vinyl ester composite were used. The used substrates are made by alternated layers of unidirectional fiber roving and chopped strand mat embedded in vinyl ester matrix; the matrix is then protected from the environmental actions by a surface veil of polyester. This configuration leads to not uniformly distributed fiber rovings.

2.1.2. Adhesives

It is important to notice that one of the most difficult challenge in the design of glass-aluminum and/or glass-GFRP adhesive joints is the selection of suitable adhesives, since in this framework there is still a lack of guidelines and standards. In this work five different adhesives, from two different manufacturers, three epoxy (*EPX*) and two acrylic (*ACR*), were selected, namely: 3M™ Scotch-Weld™ Epoxy Adhesive 7260 F/C (EPX1), Gurit Spabond 340 L V (EPX2), Gurit Spabond 345 (EPX3), 3M™ VHB ™ Tape 4941 (ACR1), 3M™ VHB ™ Tape 4950 (ACR2). The products were chosen following two criteria, as stated by Alderucci et al. [5]: (i) the adhesive should be suitable for glass-aluminum/glass-GFRP connections; (ii) the set of adhesives should be heterogeneous in load capacity, stiffness and thermal coefficient of expansion. Even if it is well known that acrylic adhesives have worse mechanical characteristics than epoxy ones, tapes could speed up the installation phase; then the authors decided to test also these products to verify their applicability.

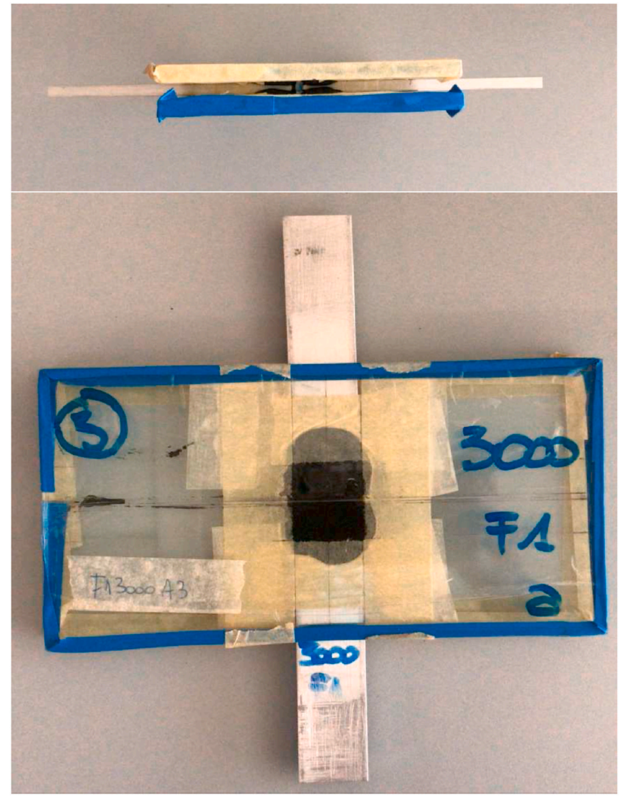

Fig. 2. Manufactured specimens.

Table 2 summarizes the technical and mechanical characteristics of the selected adhesives reported by manufacturers data sheet. Only available data are reported.

2.2. Experiments

The experimental tests consist in tensile test on adhesively bonded glass-GFRP and glass-aluminum double lap joints. Authors chose DLJ test set up in order to avoid eccentricity problems related to the single lap geometry; furthermore the selected geometry is the more suitable to represent the real joint configuration for the investigated industrial application. In particular, as mentioned, the main aim of this study is to verify the applicability of adhesive junction for a new type of window (Patent No. EP.14,015,036), in this industrial application the mobile frame is positioned inside a doubleglass cavity, joining together, thanks to the use of structural adhesives, glass panels and aluminium or GFRP substrate. In the studied application the mobile frame, put inside the doubleglass cavity, has a structural function and substitutes the external frame of the traditional windows.

Such tests allows evaluating the compatibility between glass-aluminum and glass-GFRP and comparing the mechanical behavior of the double lap joints bonded with three epoxy and two acrylic adhesives, in terms of their load carrying capacity, displacement, and stiffness.

2.2.1. Specimen geometry

The specimens were manufactured according to ASTM D3528:16 [19], the used geometry is illustrated in Fig. 1. For each experiment, three repetitions were conducted, therefore three specimens per type of test and adhesive type where produced.

The dimension of the glass panels (the minimum size provided by the manufacturer, from which the results are not affected) was 200 × 100 mm, 5 mm thick, while the dimension of the aluminum and GFRP laminates was 25.4 × 140 mm, 5 mm thick. The total overlap length where the adhesive was applied is 25.4 mm, 12.7 in each side of the

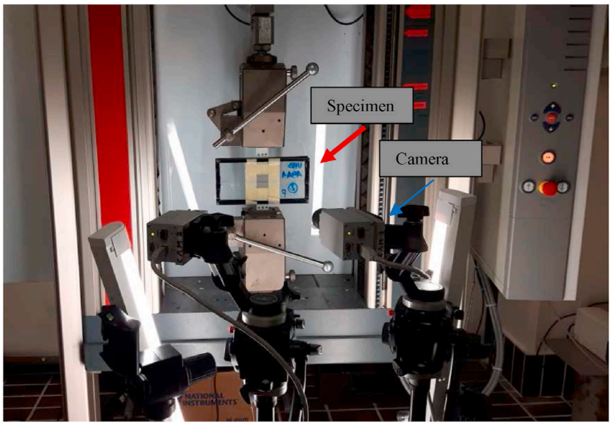

Fig. 3. Experimental set-up with specimen positioning and synchronized cameras.

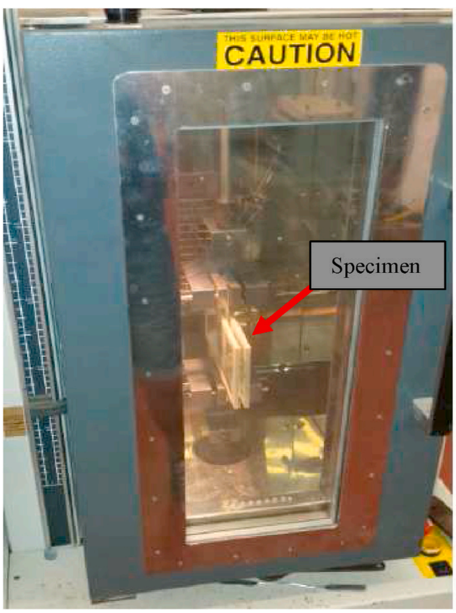

Fig. 4. Test set up at high temperature: thermostatic chamber and specimen positioning.

double lap joint.

Since the thickness of the adhesive could play a fundamental role in the behavior of the adhesive joint, the bonding thickness (*t*) recommended by each manufacturer was employed among the three epoxy adhesives, i.e. 0.3 mm for *EPX1* and 2 mm for *EPX2* and *EPX3*. With regard to the acrylic adhesives, instead, the bonding thickness depends on the tape thickness, i.e. 1.1 mm for *ACR1* and *ACR2*.

Since the study is focused on the shear strength of the joint, in the connections zone, the double-lap specimens are separated by a 2 mm interspace, where the adhesive is not present, in order to avoid the connection between the two adherents.

No surface treatments were applied to the adherents, since the effect of the superficial roughness was not investigated. All surfaces were cleansed with isopropyl alcohol, as recommended by manufacturers.

The specimens were manufactured under laboratory conditions (temperature of 18 °C, relative humidity of 70%) (see Fig. 2) and cured at room temperature for 23 days, according to specifications.

2.2.2. Test set up

All tests at laboratory conditions were carried out on a Zwick/Roell Z050 testing machine of 50 kN capacity under displacements control, with a crosshead speed of 1.27 mm/min. The test are carried out until the failure of the specimen, identified as a force drop larger than 80% with respect to the maximum one. In order to measure the displacement during the test, Two synchronized camera (Pixelink B371F 1280 × 1024, 8-bit dynamic range) were exploited to arrange an optical extensometer, with a gauge length of 110 mm. The experimental set-up is illustrated in Fig. 3.

On the other hand, the tests at high temperature were carried out through a LLOYD Instruments LR10K50, depicted in Fig. 4, with 10 kN capacity under displacements control and provided with a thermostatic chamber. The load was applied at the same rate of 1.27 mm/min used for the previous test and the specimens were again loaded up to the joint failure.

Table 3
Mechanical properties of the glass-aluminum double-lap specimens.

Series	*Fmax* (kN)		*Displacement** (mm)		*k* (kN/mm)	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation	Mean Value	Standard Deviation
EPX1	8.09	2.217	0.14	0.024	74.82	7.244
EPX2	3.93	0.609	0.16	0.041	34.05	3.510
EPX3	3.45	0.775	0.14	0.045	34.05	3.510
ACR1	0.30	0.008	10.41	0.641	0.03	0.364
ACR2	0.30	0.020	7.71	0.274	0.04	1.667

Table 4
Mechanical properties of the glass-GFRP double-lap specimens.

Series	*Fmax* (kN)		*Displacement** (mm)		*k* (kN/mm)	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation	Mean Value	Standard Deviation
EPX1	11.72	2.573	0.33	0.068	43.77	3.931
EPX2	5.86	0.964	0.23	0.009	33.66	0.087
EPX3	4.51	0.501	0.20	0.069	29.69	1.972
ACR1	0.34	0.049	12.09	0.476	0.03	0.003
ACR2	0.35	0.021	10.43	1.056	0.03	0.001

2.2.3. Test program

As mentioned before, for each test type, three repetitions were performed, thus a series of 18 specimens per adhesive type, subdivided according to the temperature conditions, were tested; three at room temperature (T_0), three at work temperature (T_w, namely 50 °C) and three at maximum service temperature ($T_m = 85$ °C for *EPX* and 90 °C for *ACR*) for each of the two adherents, as summarized in technical sheets provided by the manufacturers.

The work temperature has been chosen equal to the most frequent temperature of exposure of the selected industrial application, while maximum service temperature has been set equal to the one recommended by manufacturer, which is different for each of the tested adhesives.

3. Results and discussion

In this section, the load-elongation response and the failure modes of double-lap joints are presented and analyzed, the results are presented in terms of mean value and standard deviation, computed with respect to the three repetitions. The results are subdivided according to the used temperature conditions (T_0, T_w and T_m).

3.1. Mechanical performances of double-lap joints at laboratory conditions

Tensile tests were conducted on the double lap joints under laboratory conditions (registered temperature 20 °C and relative humidity

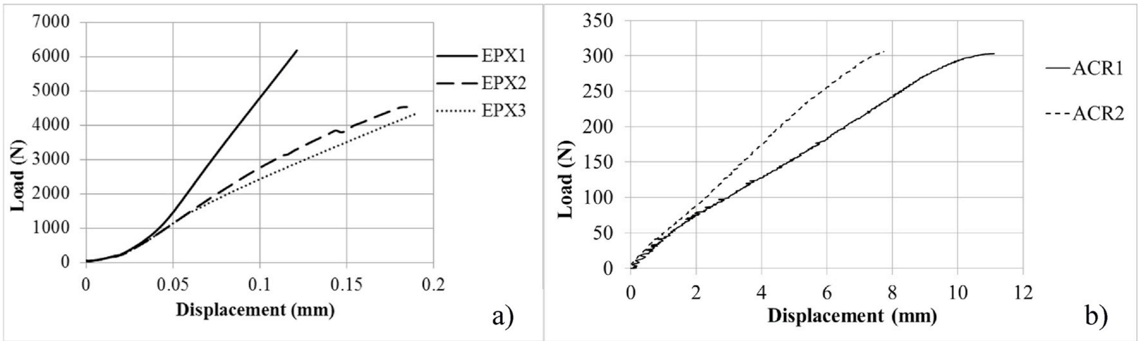

Fig. 5. Representative load-displacement curves of glass-aluminum double-lap specimens, bonded with three epoxy adhesives (a), and two acrylic adhesives (b).

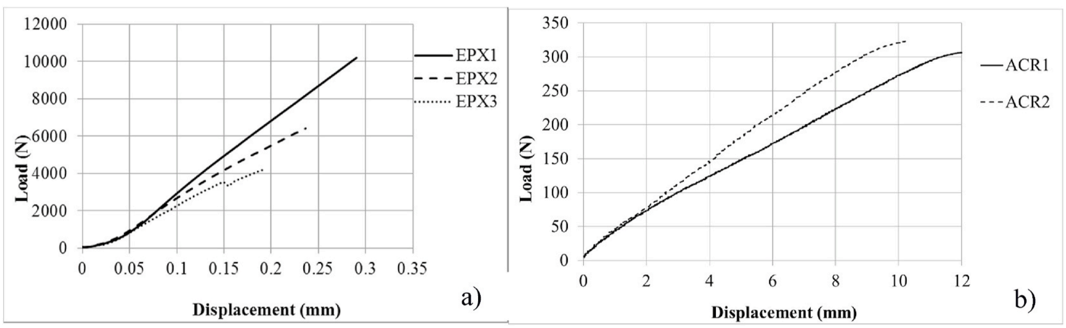

Fig. 6. Representative load-displacement curves of glass-GFRP double-lap specimens, bonded with three epoxy adhesives (a), and two acrylic adhesives (b).

50%). Tables 3 and 4 summarize the identified mechanical properties of aluminum and GFRP double-lap specimens, in terms of load carrying capacity (kN), maximum elongation (mm) and stiffness (kN/mm). The overall stiffness of the joints was computed through a linear fit of the force vs displacement curve, the fitting was limited to the initial part of the curve, before the damage initiation that produces a non-linear behavior.

The corresponding load-displacement curves for the three epoxy adhesives and for the two acrylic adhesives, are shown in Figs. 5–6.

The mechanical properties are remarkably different between epoxy and acrylic adhesive. In particular, as shown in Tables 3 and 4, epoxy adhesives have much higher load carrying capacity and stiffness, while acrylic adhesives present greater joint elongation. *EPX2* and *EPX3* had an almost similar behavior in terms of load-joint elongation and maximum load, while the best performances were achieved by *EPX1*, which bore the highest load. i.e. 10.51 kN for glass-aluminum and 14.70 kN for glass-GFRP. *ACR1* and *ACR2* showed mainly the same behavior.

Looking at the comparison between epoxy and acrylic adhesives, there is a large difference in terms of stiffness, in particular, the stiffness of epoxy joint is more than 1000 times higher than the corresponding acrylic one. The maximum load is around 10 times higher in epoxy joints while the maximum elongation is 10 times higher in acrylic ones. Therefore, the choice between epoxy or acrylic adhesives depends on the intended purpose of the junctions: if high load carrying capacity is required, epoxy ones should be used, otherwise, if a certain level of deformability is necessary, acrylic ones should be preferred.

Furthermore, from the analysis of Figs. 5–6, it turns out that epoxy joints are also influenced by the adherent, in particular, glass-GFRP joints have a load carrying capacity around 30–50% higher than the glass-aluminum ones, due to the GFRP higher superficial roughness. This influence is less evident in acrylic joints.

It is important to highlight that the different behavior of the epoxy and acrylic adhesives, due to their different chemical composition, is well known in literature and was already deeply investigated: for example Imanaka et al. [20] studied the different fracture behavior of acrilyc and epoxy adhesives, using several kinds of adhesively bonded joint, while Pereira and Morais [21] compared the strength of stainless steel adhesive joints using both epoxy and acrylic adhesives; Stazi et al. [1] analized and compared the mechanical performances of these types of adhesives at laboratory condition and after ageing treatments. But

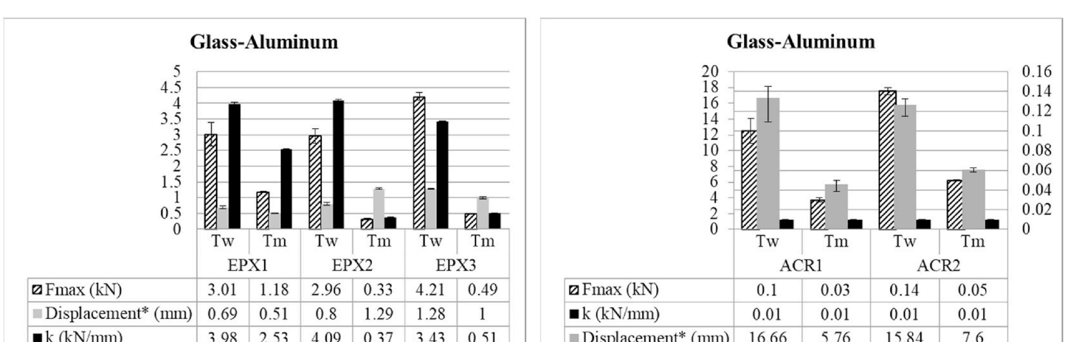

Fig. 7. Mechanical properties of the glass-aluminum double-lap specimens at high temperatures.

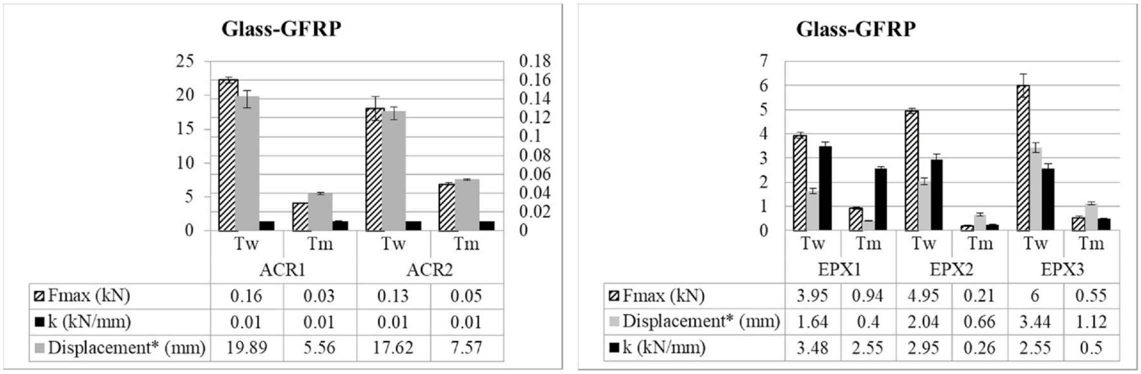

Fig. 8. Mechanical properties of the glass-GFRP double-lap specimens at high temperatures.

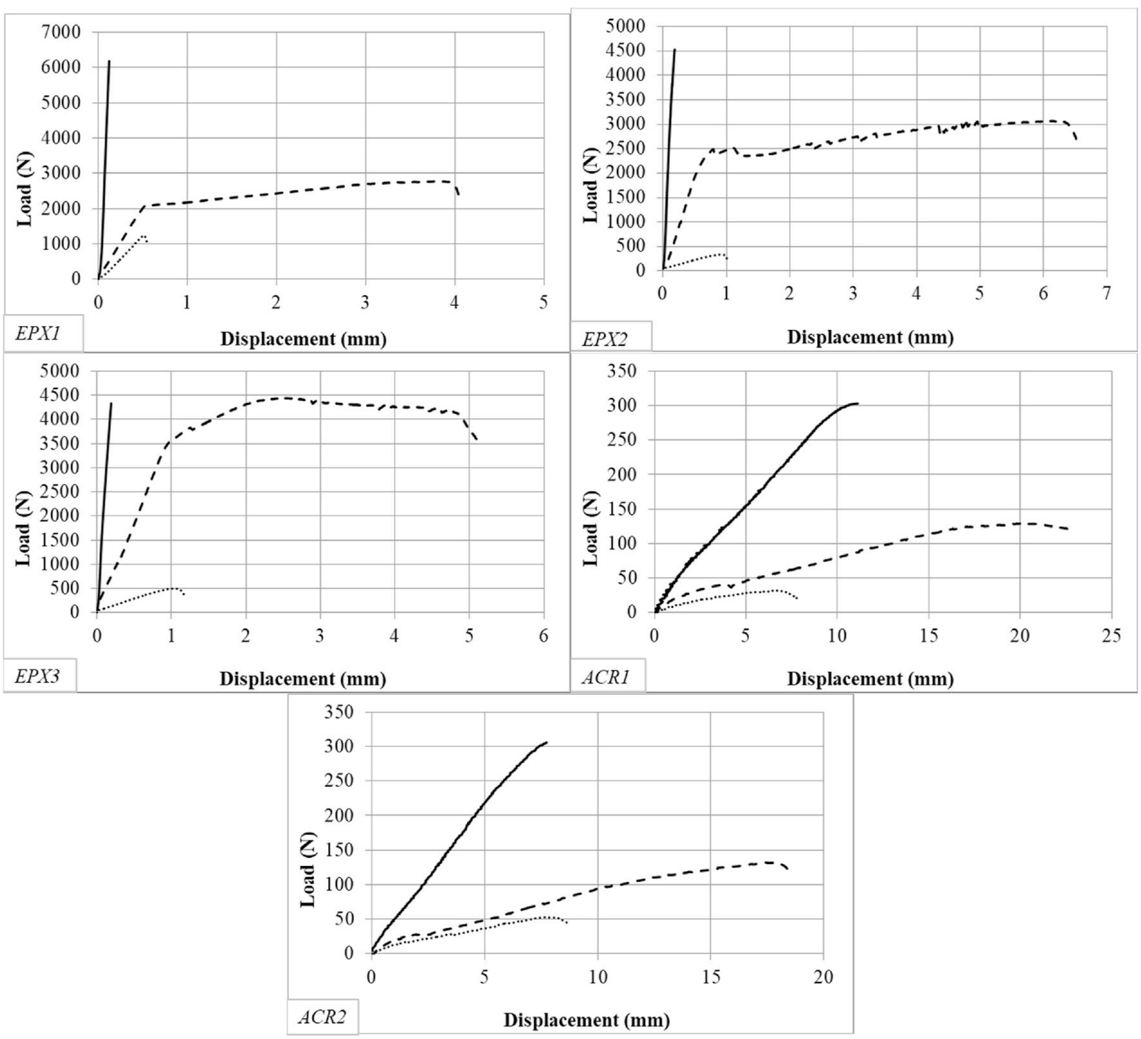

Fig. 9. Comparison between mechanical trends at different temperatures of glass-aluminum adhesive joints: T_0, solid line, T_w dashed line, T_m dotted line.

focusing on the suitability of the tested adhesives as a function of the different substrates (glass panel and mobile frame material) and to quantify the possible decay of the mechanical performances at high temperatures.

3.2. Mechanical performances of double-lap joints at high temperatures

Tensile tests were conducted on the double lap joints at work temperature ($T_w = 50$ °C) and at maximum service temperature ($T_m = 85$ °C for *EPX* and 90 °C for *ACR*). The time needed to reach the correct temperature for the tested samples was determined through a dummy sample where a thermocouple has been dipped in the adhesive; the sample was then exposed to reach T_m and T_w temperatures and the times 3 and 5 min, respectively, were determined.

The results are summarized in Figs. 7 and 8, the same mechanical properties investigated in Section 3.1 are listed.

All adhesives presented a drastic reduction of the load carrying capacity. *EPX1* presented the best behavior by maintaining almost similar

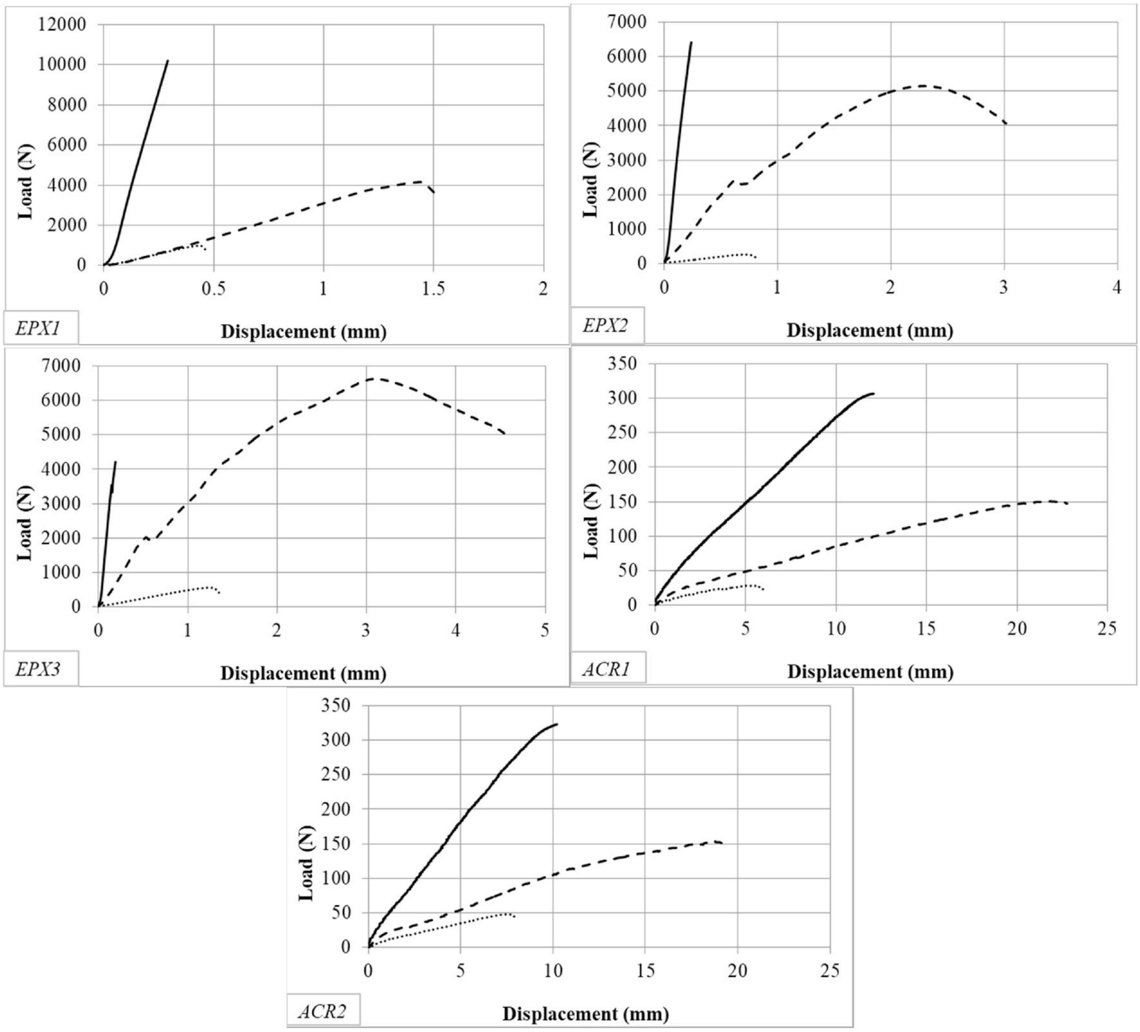

Fig. 10. Comparison between mechanical trends at different temperatures of glass-GFRP adhesive joints: T_0, solid line, T_w dashed line, T_m dotted line.

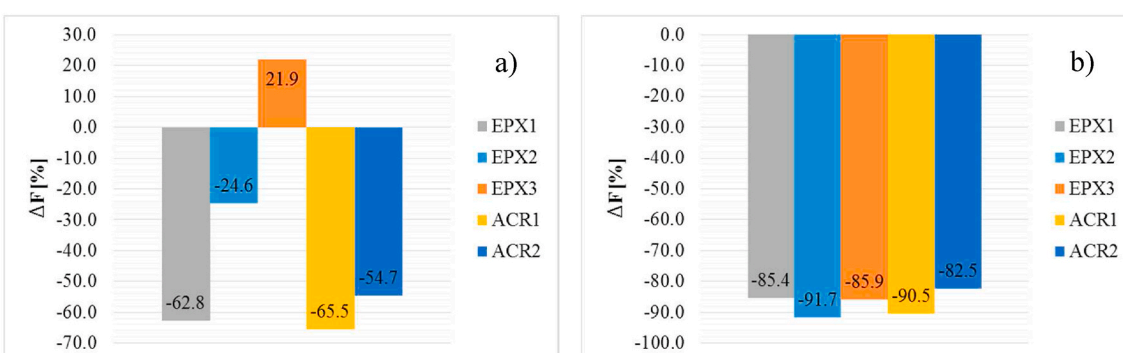

Fig. 11. Reduction of the maximum carried load of the aluminum/glass double lap joint at high temperatures: a) T_w and b)T_m.

stiffness at both temperatures, while the acrylic tapes have shown the worst behavior. The same consideration can be done for both aluminum and GFRP double-lap specimens, meaning that the performance reduction is obviously due only to the adhesive behavior.

The corresponding load-displacement curves for the three epoxy adhesives and for the two acrylic adhesives, are shown in Figs. 9–10, where the comparison between the mechanical trends at different temperatures of the tested double-lap joints with aluminum and GFRP supports, respectively, are depicted.

It can be evidenced that, for all the adhesives, there is a drastic reduction of the joint stiffness, together with an increment of the joint elongation response.

Figs. 11 and 12 show the percentage reduction of the maximum carried load of the glass-aluminum and glass-GFRP double-lap joints, respectively, with respect to the room temperature performances. *EPX2* and *EPX3* shown the best behavior at work temperature, with a contained reduction of the maximum load; in particular *EPX3* presented even an improvement of the performance, that can be explained through

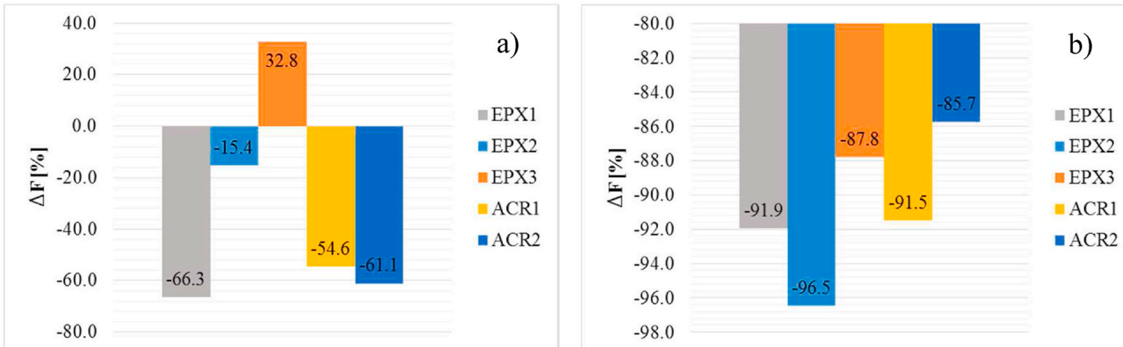

Fig. 12. Reduction of the maximum carried load of the GFRP/glass double lap joint at high temperatures: a) T_w and b)T_m.

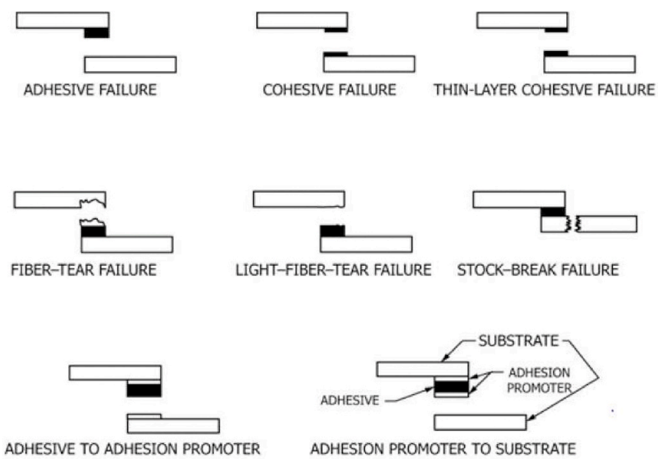

Fig. 13. Sketches representing Failure modes (adapted from Ref. [22]).

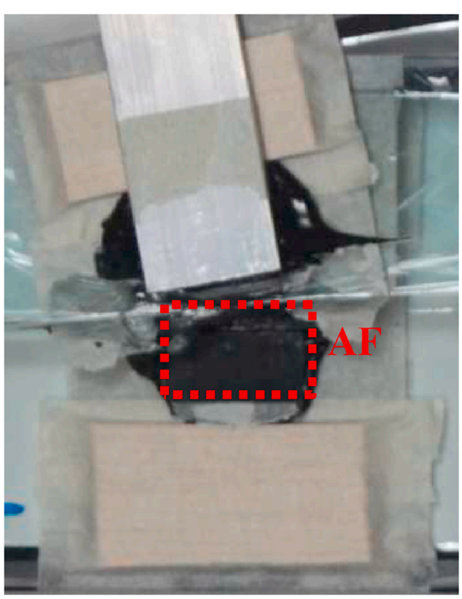

Fig. 14. Failure modes of glass-GFRP/aluminum double lap joints: adhesive (AF) failure.

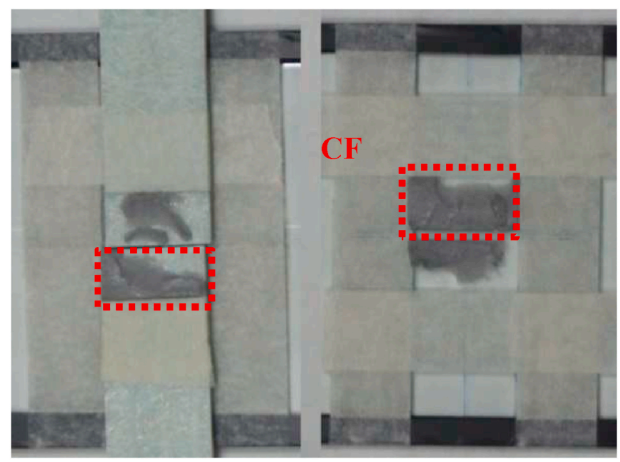

Fig. 15. Failure modes of glass-GFRP/aluminum double lap joints: cohesive (CF) failure.

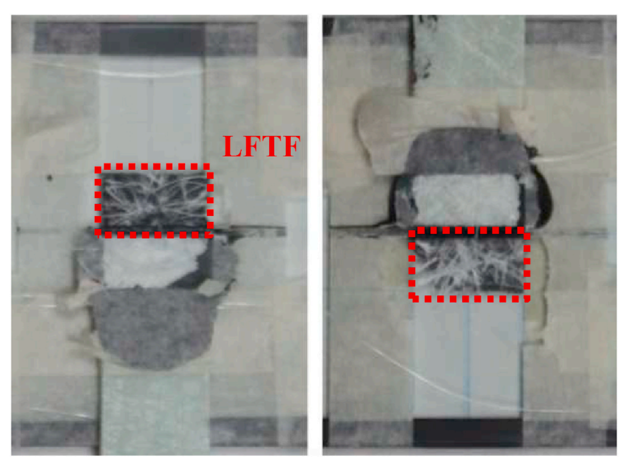

Fig. 16. Failure modes of glass-GFRP/aluminum double lap joints: light-fiber-tear (LFTF) failure.

a further adhesive catalization with the high temperature. Moreover this improvement can be associated to a change in the failure mode, as depicted in Figs. 9–10: the tested samples showed a fragile failure at T_0, while, at T_w, the failure mode changed, exhibiting a plastic deformation, which is, instead, not present at T_m; in fact all adhesives showed a drastic reduction of the load carrying capacity at T_m, that is correctly identified by the manufacturer as the maximum service temperature indeed.

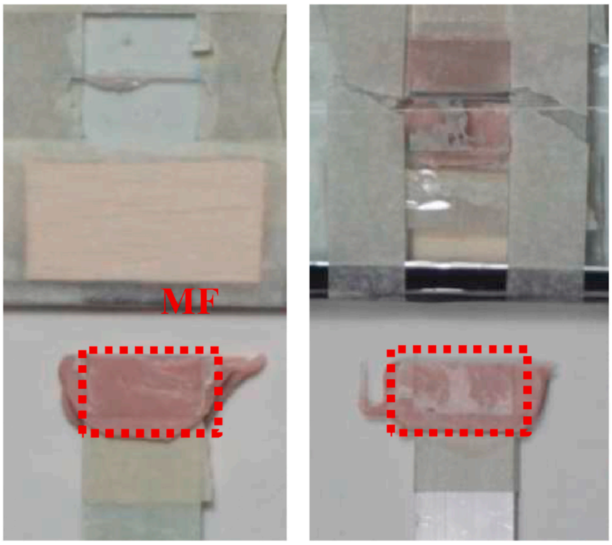

Fig. 17. Failure modes of glass-GFRP/aluminum double lap joints: mixed (MF) failure.

Table 5
Failure modes of aluminum-glass double lap joints.

Series	specimen n°	Failure mode T_0	Failure mode T_w	Failure mode T_m
EPX1	1	AF	AF	AF
	2	AF	AF	AF
	3	AF	AF	AF
EPX2	1	MF: 60% AF/40% CF	AF	AF
	2	Glass delamination	AF	AF
	3	AF	AF	AF
EPX3	1	AF	AF	AF
	2	AF	AF	AF
	3	AF	AF	AF
ACR1	1	AF	AF	AF
	2	CF	AF	AF
	3	CF	AF	AF
ACR2	1	AF	AF	AF
	2	AF	AF	AF
	3	AF	AF	AF

Table 6
Failure modes of GFRP-glass double lap joints.

Series	specimen n°	Failure mode	Failure mode T_w	Failure mode T_m
EPX1	1	LFTF	MF	AF
	2	LFTF	MF	AF
	3	LFTF	Glass failure	AF
EPX2	1	MF: 95% AF/5% CF	AF	AF
	2	MF: 95% AF/5% CF	AF	AF
	3	Glass delamination	AF	AF
EPX3	1	AF	MF	AF
	2	AF	MF	AF
	3	AF	MF	AF
ACR1	1	CF	MF	AF
	2	CF	MF	AF
	3	AF	MF	AF
ACR2	1	CF	MF	MF
	2	CF	MF	LFTF
	3	MF: 60% AF/40% CF	MF	MF

3.3. Failure modes

The occurred failure modes are herein described and analyzed, following the classification reported in ASTM D5573-99 [22]; Fig. 13 represents the possible failure modes according to D5573-99 [22].

Figs. 14–17 show the four types of failure modes observed during the tests, summarized as follows:

- the “Adhesive Failure” (AF – Fig. 14), which occurs at the interface between the adherent and the adhesive.
- the “Cohesive Failure” (CF – Fig. 15), which reveals a good compatibility between adhesive and adherends and it happens inside the adhesive layer.
- the “Light-Fiber-Tear Failure” (LFTF - Fig. 16), which is characterized by few glass fibers transferred from the adherent to the adhesive, and occurs within the GFRP adherent.
- the “Mixed Failure” (MF – Fig. 17), characterized by the superposition of two different failure modes.

Tables 5 and 6 summarize the failure modes of glass-aluminum and glass-GFRP joints, respectively. Glass-Aluminum specimens presented mainly AF, while glass-GFRP showed LFTF or CF, showing a greater compatibility of the bonding system at T_0.

For both epoxy and acrylic adhesives, the adherence with the laminates is deteriorated by the exposition to high temperatures, i.e. the majority of the observed failures became AF, at increasing temperatures.

4. Conclusions

In this paper an experimental campaign to study the bonding connection of glass-aluminum and glass-GFRP through different adhesives (three epoxy and two acrylic) is presented. Tensile tests were performed in order to verify the compatibility of the adhesive joint for this particular type of junction. The compatibility of the selected materials and the mechanical responses to global stresses were verified. Furthermore, the degrading mechanisms caused by high temperature are also investigated through specific tests.

4.1. Several outcomes are herein summarized

– Tensile tests demonstrated the compatibility of the glass-GFRP and glass-aluminum bonding system, and the best mechanical performance of the first epoxy adhesive (*EPX1*) was observed, for both adherents.
- Epoxy joints are influenced by the adherent, in particular the load carrying capacity is higher in GFRP joints with respect to the aluminum ones, due to the GFRP higher superficial roughness; instead in acrylic joints this influence is less evident.
- In an unexpected way *EPX3*, presented an improvement of the performance at work temperature, that could be explained through a further adhesive catalization with the high temperature. All the adhesives presented a drastic reduction of the load carrying capacity at T_m.
- Glass-aluminum specimens presented adhesive failure, while glass-GFRP showed LFTF or CF, showing a greater compatibility of the bonding system at T_0.
- Exposition to high temperatures deteriorates the adhesion between laminates and adhesive, changing in many cases the failure modes to AF.

Finally, both at room temperature and high temperatures the highest load carrying capacity was reached by the epoxy adhesives, while, on the other hand, the highest load elongation was obtained with the acrylic ones. Therefore, if a structural performance is needed, epoxy adhesive are more appropriated hybrid joints with glass-aluminum and glass-GFRP. Furthermore, even if exposition to high temperatures leads to a decay of the joint mechanical performances, which has to be taken into account with an appropriate safety factor in the design phase, the joint elongation for epoxy adhesives is contained within a suitable functionality limit.

Acknowledgments

A special acknowledgment goes to Engineer Vanessa Terlizzi for the important contribution in performing the tests and elaborating data.

References

[1] Stazi F, Giampaoli M, Rossi M, Munafo P. Environmental ageing on GFRP pultruded joints: comparison between different adhesives. Compos Struct 2015;133:404–14.

[2] Keller T. Recent all-composites and hybrid fiber-reinforced polymer bridges and buildings. Prog Struct Eng Mater 2001;3:132–40.

[3] Godat A, Legeron F, Gagne V, Marmion B. Use of FRP pultruded members for electricity transmission towers. Compos Struct 2013;105:408–21.

[4] Appelfeld D, Hansen CS, Svendsen S. Development of a slim window frame made of glass fibre reinforced polyester. Energy Build 2010;42:1918–25.

[5] Alderucci T, Terlizzi V, Urso S, Borsellino C, Munafò P. Experimental study of the adhesive glass-steel joint behavior in a tensegrity floor. Int J Adhesion Adhes 2018;85:293–302.

[6] Foraboschi P. Behavior and failure strength of laminated glass beams. J Eng Mech 2007;133:1290–301.

[7] Hollaway LC. A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. Construct Build Mater 2010;24:2419–45.

[8] Turvey GJ. Testing of pultruded glass fibre-reinforced polymer (GFRP) composite materials and structures. Woodhead Publishing Ser Civ Struct Eng; 2013. p. 440–508.

[9] de Castro J, Keller T. Ductile double-lap joints from brittle GFRP laminates and ductile adhesives, part I: experimental investigation. Composites B 2008;39:271–81.

[10] Kim H-Y, Lee S-Y. A steel-reinforced hybrid GFRP deck panel for temporary bridges. Construct Build Mater 2012;34:192–200.

[11] Borowicz DT, Bank LC. Behavior of pultruded fiber-reinforced polymer beams subjected to concentrated loads in the plane of the web. J Compos Construct 2010;15:229–38.

[12] Machalická K, Eliášová M. Adhesive joints in glass structures: effects of various materials in the connection, thickness of the adhesive layer, and ageing. Int J Adhesion Adhes 2017;72:10–22.

[13] Giampaoli M, Terlizzi V, Rossi M, Chiappini G, Munafò P. Mechanical performances of GFRP-steel specimens bonded with different epoxy adhesives, before and after the ageing treatments. Compos Struct 2017;171:145–57.

[14] Marquesa EAS, da Silva LFM, Banea MD, Carbasa RJC. Adhesive joints for low- and high-temperature use: an overview. J Adhes 2015;91:556–85.

[15] Viana G, Costa M, Banea MD, da Silva LFM. A review on the temperature and moisture degradation of adhesive joints. Proc IME J Mater Des Appl 2017;231:488–501.

[16] da Silva LFM, Adams RD, Gibbs M. Manufacture of adhesive joints and bulk specimens with high temperature adhesives. Int J Adhesion Adhes 2004;24:69–83.

[17] Uni En 755-2. Aluminium and aluminium alloys - extruded rod/bar, tube and profiles - Part 2: mechanical properties. 2016.

[18] ASTM D638. Standard test method for tensile properties of plastics. 2014.

[19] ASTM D3528-16 Standard test method for strength properties of double lap shear adhesive joints by tension loading.

[20] Imanaka M, Liu X, Kimoto M. Comparison of fracture behavior between acrylic and epoxy adhesives. Int J Adhesion Adhes 2017;75:31–9.

[21] Pereira AB, de Morais AB. Strength of adhesively bonded stainless steel joints. Int J Adhesion Adhes 2003;23:315–22.

[22] ASTM D5573-99. Standard practice for classifying failure modes in fiber reinforced plastic (FRP) joints.