THERMAL ANALYSIS AND MECHANICAL CHARACTERIZATION OF GFRP JOINTS

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Abstract
Wind energy represents an interesting sector in the field of renewable energy in particular as regards to the use of innovative materials such as CFRP and GFRP materials.
The thermographic technique can be a valuable tool in this application field because allows a non-contact inspection of large areas, as for example occurs for remotely controls of the blades of large wind turbines.
The mechanical characterization tests of GFRP adhesive joints were preceded by lock-in thermography tests in order to detect bonding defects, or more generally, defects that might compromise the mechanical strength of joints.

1 Introduction
The increased development of structural adhesives for bonding applications has, nowadays, induced a continuously diffusion of adhesive joints instead of the traditional mechanical connections used in the past, as nailing, bolting, etc. many advantages can be generally offered by adhesive joints from a mechanical and economical point of view, due to their flexibility in design, lower maintenance costs and capacity to reduce unfavourable stress concentrations as usually occurs in the bolted or riveted joints. this represents for designers an attractive alternative to the traditional joints and connections. a poor knowledge of the mechanical behaviour of adhesive joints, however, as well as inadequate production processes causing possible defects in the material or poor quality of bonding at the interface, still represent some risk factors for most applications [1], [2]. this emphasizes the importance of a preliminary knowledge of the physical condition of adhesive joints [3], [4]. a cautious approach should be also maintained with respect to the mechanical results of adhesive joints published in the literature. these results strictly depend on different factors as:

- the selection of the adhesive material;
- the joint design (i.e. the dimensions, the shape, the overlap length, etc.);
- the surface preparation of the adherends;
- the quality of bonding.

in this sense, the thermographic technique can represent a valid quality inspection tool of wide distant areas without an effective contact, as occurs, for example, with composite wind turbines of big dimensions when possible critical defects are necessary to be detected.
This work presents the results of an experimental investigation aimed to analyse the efficiency of the thermographic lock-in technique [5], [6] as nondestructive method of evaluation of the

integrity of adhesive glass fiber-reinforced polymer (GFRP) composite joints, typically adopted for the construction of blades and components of wind turbines. A nondestructive control, indeed, permit to monitor the presence of micro and/or macro-defects created inside the material during the production process, as well as inadequate bonding between adherends, which would invalidate the global mechanical properties of adhesive joints. After performing this qualitative control, the experimental results of a mechanical investigation on single lap joints are here presented, whose repeatability is representative of the integrity-condition of the material and interfaces.

2 Materials and process

The material and relative specimens were obtained through the vacuum infusion resin process. Two different sets of composite materials with epoxy-type (i.e. EC 157 by ELANTAS) or vinylester-type (AME6000 INF by ASHLAND COMPOSITE POLYMERS) resins were taken into account, reinforced with a double layer of quadriaxial glass fiber of the type 0°/+45°/90°/-45°. Furthermore, a modified and thixotropic bi-component epoxy resin (ADH 90.91 by ALTANA ELECTRICAL INSULATION) was here used as structural adhesive. The preparation of the adherends before the bonding phase was extremely important for a good outcome of joints and validation of their mechanical properties. After a preliminary surface preparation and cleaning of panels, as recommended by the standard ASTM D2093 as long as a break free surface was obtained, the adhesive and tabs were accurately applied prior to cutting the final specimens. A special attention was paid to the bonding process (object of interest of the thermographic study), as a proper adhesive bonding was crucial for the final mechanical behaviour of the joints.

3 Lock-in Thermography

Lock-in thermography is based on thermal waves generated inside the specimens by submitting them to periodic thermal stimulations. In the case of a sinusoidal temperature stimulation of a specimen, highly attenuated and dispersive waves are found inside the material [5], [6], [7], [8].

In a semi-infinite isotropic solid, heated with a uniform sinusoidal heat source over time *t*, the temperature distribution can be obtained solving the equation:

$$\frac{\delta^2 T(x,t)}{\delta x^2} - \frac{1}{\alpha}\frac{\delta T(x,t)}{\delta t} = 0 \qquad x > 0,\ t > 0 \tag{1}$$

where x is the depth and α is the thermal diffusivity.

The solution of equation (1) is:

$$T(x,t) = T_0 e^{-x/\mu} \cos(2\pi x/\lambda - \omega t) \tag{2}$$

where μ is the thermal diffusion length

$$\mu = \sqrt{\frac{2k}{\rho c \omega}} \tag{3}$$

with thermal conductivity k, mass density ρ, specific heat c, modulation frequency ω, while T_0 is the temperature on the surface of specimen at $t=0$ and $\lambda = 2\pi\mu$ is the wave length.

The phase wave equation (2) is related to the depth x as follows:

$$\varphi(x) = \frac{2\pi x}{\lambda} = \frac{x}{\mu} \tag{4}$$

In the case of phase images, the depth range is considered to be about twice the width. In the equation (3) , μ is related to the inverse of ω, this means a low modulation frequency will probe deeper [7], [8].

4 Specimen geometry and set-up

The sample geometry, preparation and conditioning agree with recommendations of standard ASTM D3165 [9]. The shape and dimensions of the specimens are reported in Figure 1.
All specimens were tested on a 50-kN mts machine, model alliance RT/50, in displacement control mode, with a cross-head displacement rate of 1.27mm/min. A uniaxial extensometer with a gage length of 12.5 mm was used to monitor the deformation of the joint in the overlap length (Figure. 2(a)).

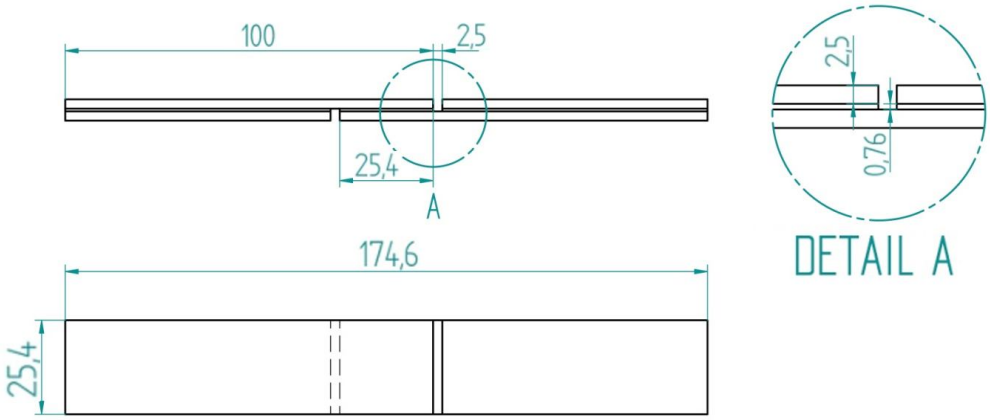


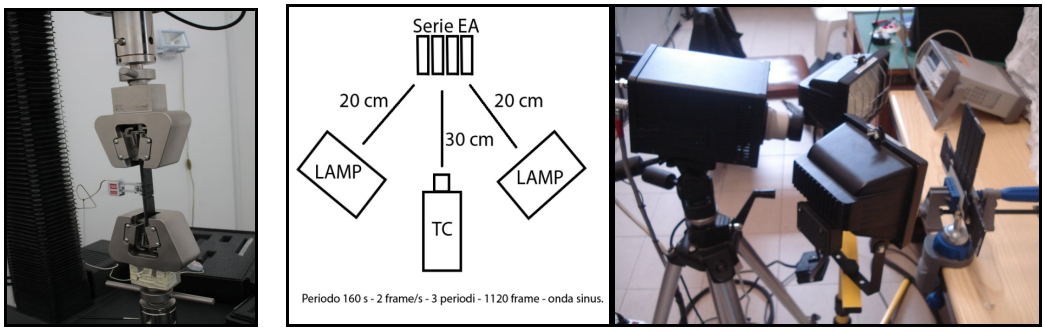
Figure 1. Geometry of single lap joint according to ASTM D3165

The thermography data have been acquired via the differential IR camera DeltaTherm 1560 (DT) made by StressPhotonics (USA) with thermal sensitivity (NETD) < 18 mK and based on a InSb photonic detector with 320×256 pixels.
Two halogen lamp were used as thermal source for lock-in thermography tests (1000 W totally) and DeltaTherm software by Stressphotonics was used to processing thermal data.
Preliminary tests were carried out on joints with characteristic defects such as debonding and thickness variation, in order to obtain the optimum set-up to final tests on adhesive joints.
Lock-in thermography tests were carried out on 20 specimens for each sets of composite materials with epoxy-type (EA) or vinylester-type (VA) resins.
Figure 2 shows the set-up used for thermography tests.

5 Results

5.1 Thermography tests

The experimental lock-in thermography apparatus allows to observe the effects magnitude and phase of thermal waves on the specimen. The phase image is relatively independent of local optical infrared surface features. Furthermore, lock-in thermography is able to give more precise measurements in the evaluation of materials (as e.g. composites) characterized by low thermal diffusivity.



(a) (b)

Figure 2. Mechanical tests set-up (a), thermography lock-in set-up (b)

Preliminary tests on specimens with known defects were performed in order to establish the best experimental set-up and calibrate the tests lock-in thermography parameters such as the thermal excitation frequency and the acquisition frequency of the thermocamera. More in detail, specimens with debonding zones, metallic inserts and different thickness were here considered.

Table 1 shows the tests parameters used during the preliminary tests.

An excitation frequency of 0.00625 Hz provides the best results when detecting all the above mentioned defects, whereas any differences were observed for the two considered resins.

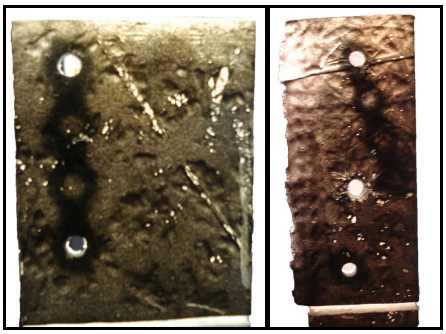


Figure 3. Specimens used for preliminary thermographic tests

Test number	*Period [s]*	*Frequency [Hz]*	*Cycle number*	*Frame acquired*
1	30	0.03333	3	180
2	60	0.01667	3	360
3	90	0.01111	3	540
4	120	0.00833	3	720
5	160	0.00625	3	960
6	200	0.00500	3	1200
7	250	0.00400	3	1500
8	300	0.00333	3	1800
9	400	0.00250	3	2400

Table 1. Lock-in experimental parameters

Figure 4 shows the phase image of the specimen used during the preliminary tests. The debonding zones and the metallic inserts are clearly evident. Figure 4 plots also the phase along a transversal direction in the specimen. A slight variation of the phase signal (approximately equal to 1°), is observed along the profile in correspondence of defect zones,. A net variation of the phase signal is otherwise obtained when the considered profile passes through the zone with different thermal properties such as the metallic insert.

Thermographic tests on adhesive joints were carried out using the experimental parameters obtained by preliminary tests. The specimens were initially painted with matt black paint in order to uniform the emissivity of the treated surfaces and avoid reflections due to heat sources placed near the specimens during the test.
The results obtained show a good bonding and a total absence of defects in the bonding zones. Figure 5 shows the phase image of four adhesive joints and the hidden notch placed to 2.5 cm. These results confirm the use of good parameters to detect defects into the whole depth of the adhesive joints. In particular, in the bonding zones, a phase signal variation less then 1° was observed. A significant signal phase variation was otherwise obtained due to the superficial profile variation of the first resins layers in the adhesive joints.

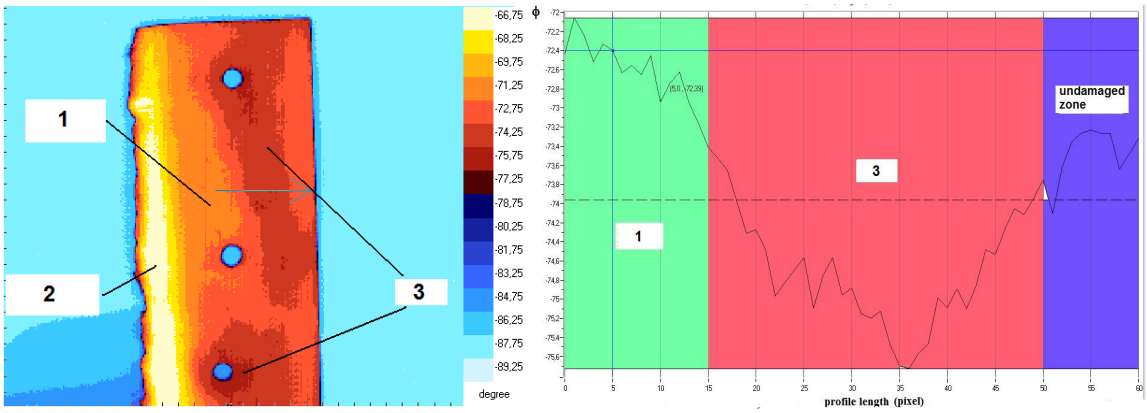


Figure 4. Lock-in phase image and signal phase variation on the specimen in presence of: 1 debonding zones, 2 thickness variation, 3 metallic insert

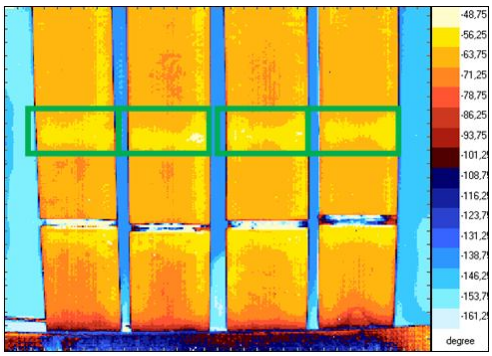


Figure 5. Lock-in thermography phase image of 4 adhesive joints (EA), (f=0.00625 Hz).

5.2 Mechanical tests
For each mechanical test, the maximum shear strength τ_{max}, was determined as follows

$$\tau_{\max} = \frac{P}{B \cdot L} \tag{5}$$

where P is the failure load expressed in [N], while B and L are the width and the length of the joint in the overlap zone, expressed in [mm]. Results are reported in Tabb. 2 and 3 for the two sets of joints named EA and VA, respectively. By analyzing the results from a statistical point of view (standard deviation and coefficient of variation %), a slight dispersion in the load and shear strength values can be observed with respect to the main values for both sets of joints. The entity of the dispersion for each mechanical property is also confirmed by the failure mode variability of the specimens for both sets of joints. For this reason, it is worth noticing as different single or mixed failure modes may interest an adhesive joint , i.e.: the *adhesive*

failure at the adhesive-adherend interface (*ADH*), the *cohesive failure* within the adhesive (*COH*), the *thin-layer cohesive failure* close to the adhesive-substrate interface (*TLC*), the *fiber-tear failure* within the composite matrix (*FT*), the *light-fiber-tear failure* within the composite matrix near the surface (*LFT*), or a combination of them. Based on what above mentioned, by analyzing the failure modes for the EA-joints, lower values of shear strength seem to be related to mixed failures of the type *ADH* and *LFT* (Fig.6). As also expected, an increasing percentage of adhesive failure decreases the shear strength of the joint, whereas more resistant joints are interested by TLC (Fig. 7a) and/or LFT failure (Fig. 7b) with different proportions. A lower dispersion of results is otherwise obtained for VA-joints characterized by a prevailing TLC failure combined with different percentages of LFT failure (Figure 8).

Specimen	**L [mm]**	**B [mm]**	**P_{max} [kN]**	**τ_{max} [MPa]**	**Failure mode**
EA-01	25.00	25.00	3.38	5.41	LFT+ADH
EA-02	25.00	24.73	5.88	7.11	TLC+LFT
EA-03	25.45	25.20	3.76	5.86	LFT
EA-04	24.51	25.10	2.87	4.67	ADH+LFT
EA-05	25.45	24.27	3.91	6.33	LFT
EA-06	24.72	25.13	4.08	6.57	FT
EA-07	25.40	24.60	3.50	5.61	LFT+ADH
EA-08	25.40	24.60	3.89	6.22	LFT
EA-09	23.70	25.00	3.77	6.37	FT
EA-10	23.68	24.50	4.08	6.71	FT
EA-11	24.81	24.53	5.20	8.54	TLC
EA-12	25.32	24.87	3.84	6.10	LFT
EA-13	24.03	24.73	3.04	5.12	LFT+ADH
EA-14	25.00	24.53	4.09	5.65	LFT+ADH
EA-15	24.71	24.70	4.66	6.89	TLC
EA-16	24.73	25.70	3.90	5.52	LFT+ADH
EA-17	23.91	25.20	2.85	4.73	ADH+LFT
EA-18	24.75	25.27	5.25	7.33	TLC
EA-19	25.43	25.03	3.77	5.93	LFT
EA-20	23.86	25.30	4.19	6.01	LFT
Main			4.00	6.10	
Standard dev.			0.80	0.90	
CV [%]			19.35	14.98	

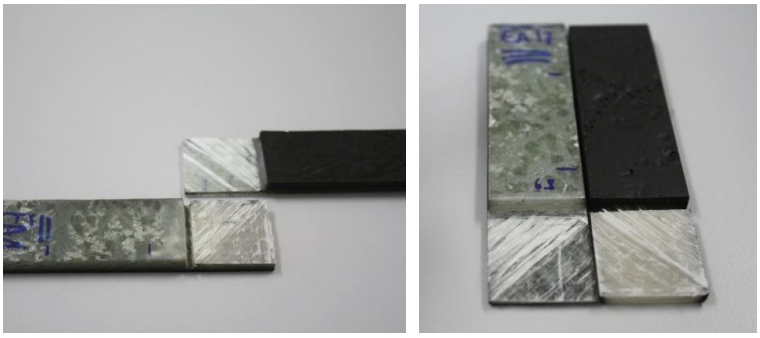
Table 2. Mechanical properties of EA-joints

6 Conclusions

This work presents results from an experimental study on the efficiency of thermographic techniques as nondestructive testing of adhesive GFRP joints. The primary objective of this investigation was to verify whether an effective bonding process of a resin is applied at the interface between adherends of a composite joint. The relation between possible defects in the bonded interface of a joint and its mechanical adhesive properties was then evaluated. Two different adhesives, i.e. epoxy and vinylester resins, were adopted in this investigation, and a double qualitative and quantitative approaches were examined for a better understanding of the problem. More in detail, the thermographic lock-in method provided the experimental basis to examine the joints on a quality level, while a quantitative understanding of their structural shear behavior was obtained through a mechanical characterization testing.

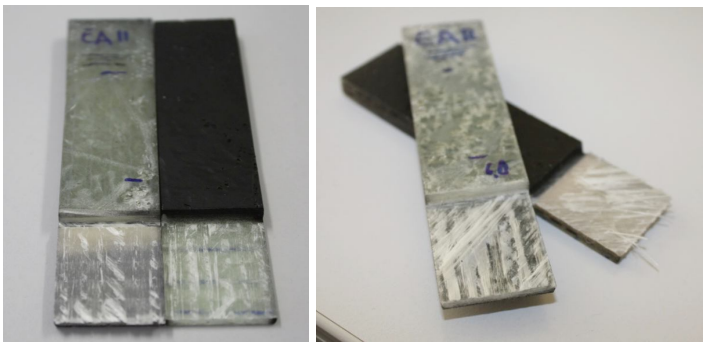
Specimen	L [mm]	B [mm]	P_{max} [kN]	τ_{max} [MPa]	Failure mode
VA-01	24.37	24.37	2.77	4.62	ADH+LFT
VA-02	24.79	24.79	3.11	4.96	TLC+LFT
VA-03	25.39	25.39	3.13	4.91	TLC+LFT
VA-04	25.39	25.39	3.05	4.78	TLC+LFT
VA-05	24.83	24.83	2.84	4.58	ADH+LFT
VA-06	24.42	24.42	3.39	5.55	TLC+LFT
VA-07	24.94	24.94	3.14	5.00	TLC+LFT
VA-08	24.53	24.53	3.20	5.20	TLC+LFT
VA-09	24.53	24.53	3.83	6.09	TLC
VA-10	24.53	24.53	3.25	5.17	TLC+LFT
VA-11	24.80	24.80	2.94	4.70	ADH+LFT
VA-12	24.98	24.98	3.09	5.01	TLC+LFT
VA-13	24.31	24.31	2.91	4.97	TLC+LFT
VA-14	24.42	24.42	3.57	5.79	TLC
VA-15	24.32	24.32	2.70	4.44	ADH+LFT
VA-16	24.84	24.84	3.05	4.98	TLC+LFT
VA-17	24.90	24.90	2.89	4.67	ADH+LFT
VA-18	24.79	24.79	3.03	4.85	TLC+LFT
VA-19	25.20	25.20	3.03	4.77	TLC+LFT
VA-20	24.92	24.92	3.32	5.37	TLC+LFT
Main			3.10	5.00	
Standard dev.			0.30	0.40	
CV [%]			8.59	8.27	

Table 3. Mechanical properties of VA-joints



(a) EA-04 (b) EA-17

Figure 6. Mixed LFT and ADH failure modes



(a) EA-11 (b) EA-012

Figure 7. TLC (a) and LFT (b) failure modes

Figure 8. LFT failure mode for the joint VA-07

Some preliminary lock-in tests were performed on damaged specimens in order to verify the good capability of this nondestructive technique when detecting defects as an inadequate bonding and preparation of surfaces, or the presence of voids, bubbles or inclusions within the material. A good quality in the bonding process was generally noticed for all the undamaged specimens, whereas most differences in the mechanical properties and failure modes were related to the geometry of the joints, i.e. a variable thickness of adhesives and adherends, or a slight stiffness imbalance between the two adherends of a joint due to a non uniform resin infusion process of the composite panel. These factors, indeed, may cause some stress concentrations or load eccentricities in the overlap zone, thus enabling an early failure or a global bad behavior of some specimens.

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