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Fatigue behavior of hybrid and bonded single lap joints made of composite material

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Abstract

Joining of composite materials can be performed with different techniques and, in particular, through mechanical fasteners, bonding, hybrid solutions. In last years, hybrid (bolted/bonded) joints are attracting the interest of several companies and scientific community, since the use of both techniques permit to overcome some critical aspects connected to the separate usage of adhesive and bolts, i.e., negative effects of the environmental conditions on adhesive, localized stresses at the notch. This paper aims to improve the knowledge about the fatigue behavior of hybrid CFRP (Carbon Fiber Reinforced Polymer) joints. For the purpose, experimental fatigue and static tests are performed on hybrid and bonded joints and the results herein discussed. Results are post-processed with the main goal to highlight the benefits led to the hybrid technique with respect to the bonding one.

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1. Introduction

Composite materials are attracting several engineering fields thanks to their advantages, in terms of specific strength with respect to conventional (metallic) materials. However, their application can become particularly challenging due

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to the several aspects concerning the joining operations, notch effects, environmental conditions, barely visible damages and so on (Sepe et al. (2017)).

Joining of composite laminates can be performed through mechanical fastening, adhesive bonding, or a combination of both (Chowdhury et al. (2015), Kelly (2006)). Adhesive bonding does not need drilling operations and it allows the distribution of the load over a larger area with respect to mechanical joints (Armentani et al. (2020), Greco et al. (2019), Li et al. (2012), Abdelkerim et al (2019)). In contrast, adhesive joints are sensitive to environmental conditions, humidity, in-service temperature and surface treatment (Mariama et al. (2019)). The use of both mechanical fastening and adhesive layer is often adopted to take advantages by both techniques and to improve the safety against possible not-expected damages and defects that can lead the joint to the collapse (Lamanna et al. (2012), Lamanna et al. (2014), Armentani et al. (2018), Sadowski et al. (2011)). According to the literature, hybrid (bolted/bonded) joints are attracting the interest of several companies and researchers: literature can also count on the proposal of different modelling strategy to simulate the joint structural behavior (Emami Geiglou et al. (2018), Armentani et al. (2020), Greco et al. (2019), Caputo et al. (2011)). The advantages brought by the mechanical fastening counterpart is given by the possibility to align the two components to connect. Moreover, according to the experimental evidence, the failures affecting the bonded connections during an accidental crash may lead to the separation of the parts. As a result, hybrid joints become even more attractive, especially for the automotive field. Contrary, the lower levels of load transferred to the connections and the increase in weight, get the use of mechanical fasteners not particularly attractive and common in the aerospace, even if some applications can be found where the loads are significantly high, permitting, at the same time, to arrest possible damages. In addition, it must not be ignored the problem that a drilling operation can introduce especially in composite materials. Even if the literature can count on several research activities on the joining operations of structural components, the part related to the joining of composite material needs to be still examined in depth, particularly under a fatigue (Samaei et al. (2018), Esmaeili et al. (2015)) point of view.

This paper deals with an experimental investigation of hybrid and bonded single lap joints made of CFRP (Carbon Fiber Reinforced Polymer) under quasi-static tensile and fatigue loading conditions. The adherends were manufactured by co-curing carbon prepreg. The backface strain (BFS) measurement technique (Solana et al. 2010) was used to detect and monitor the initiation of the first cracks in the adhesive layer of the joints. BFS technique allows the in-situ monitoring of crack initiation and evolution under both quasi-static and fatigue loading conditions. It consists in equipping the test article under investigation with two strain gauges, placing them in specific locations of the joint. Subsequently, cracks propagation was monitored through both digital camera and liquid penetrant method. During the tests, loads and displacements were monitored and the response of both adhesive and hybrid joints configurations compared.

Nomenclature

a	adherends overlap length
A_{ff}	gauge length
d_1	hi-lok diameter
d_2	hi-lok head diameter
E_{11}	longitudinal Young modulus
E_{22}	in-plane transverse Young modulus
E_{33}	out-of-plane transverse Young modulus
h	adherend width
L	adherend length
N_R	cycles to rupture
R	fatigue stress ratio
s_1	adherend thickness
s_2	adhesive thickness
S_{12}	in-plane shear strength
X_t	longitudinal tensile strength
X_c	longitudinal compressive strength
Y_t	transverse tensile strength

2. Materials and method

Two types of joints were manufactured: bonded and hybrid bonded/bolted ones, Fig. 1.

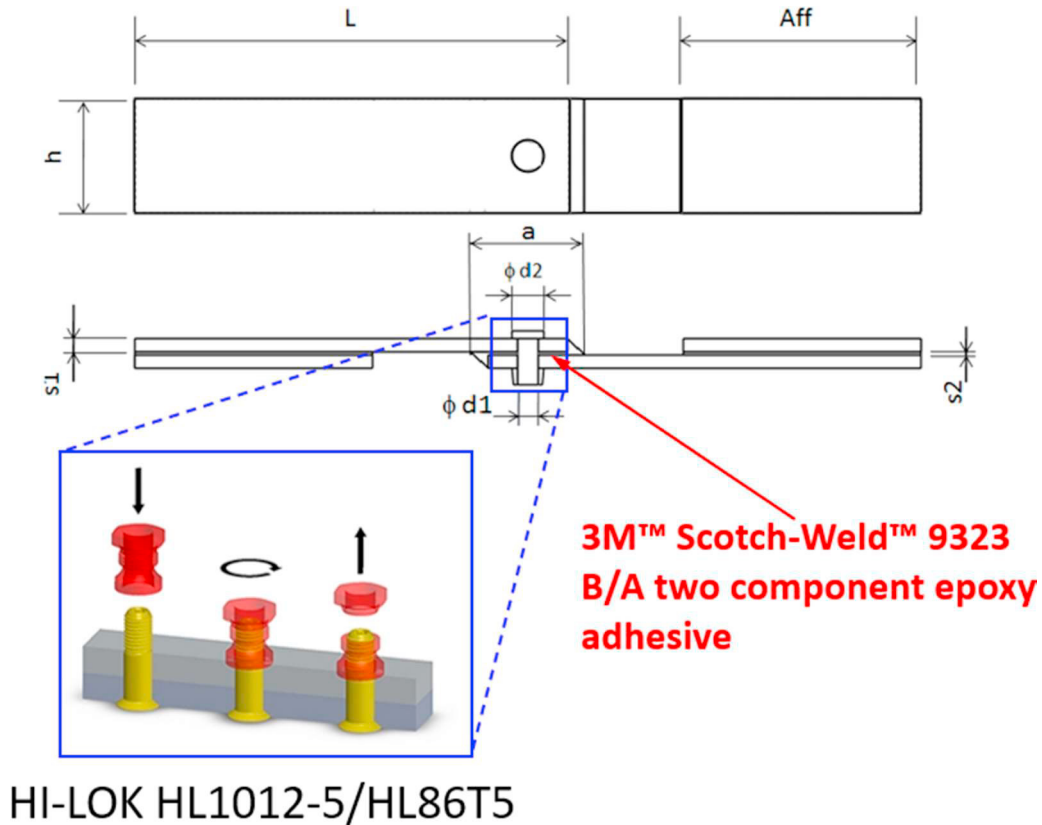


Fig. 1. Specimens.

According to Fig. 1, $h = 36$ mm, $a = 36$ mm, $L = 136.5$ mm, $d_1 = 6.35$ mm, $d_2 = 11$ mm, $Aff = 75$ mm, $s_1 = 5$ mm, $s_2 = 0.2$ mm. For the bonded area, 3M™ Scotch-Weld™ 9323 B/A two component epoxy adhesive was used, while for the bolt, HI-LOK HL1012-5/HL86T5 capable to provide a controlled torque. Before gluing, adherend surfaces have been prepared. Adherend interfaced surfaces were accurately cleaned through acetone and mechanically abraded with alumina sandpaper (220 grit) and after that a second degreasing treatment with propanol was performed. The adhesive cure was performed at room temperature for 14 days. The thickness of adhesive was controlled up to 0.2 mm by means bonding device.

The surface treatment and bonding operations were performed for both bonded and hybrid joints, which strength depends significantly on the surface treatment of the adherends. The adherends were manufactured by co-curing 16 HexPly® 8552-AS4 Carbon prepreg CFRP laminae with a stacking sequence of $[0/45/90/-45]_{2s}$. Lamina material properties are shown in Table 1.

Specimens were tested under static and fatigue loads. Specifically, for the former, an electromechanical test machine, Zwick/Roell 250, equipped with a 250 kN load cell, was used to carry out the tests in displacement control, at a crosshead speed of 2 mm/min. Tests were performed at room temperature. Two tests for each specimen type were performed. Concerning the latter, a universal testing machine INSTRON 8502 equipped with load cell of 50 kN was used.

Table 1. Mechanical properties of HexPly® 8552-AS4 carbon prepreg lamina.

Material properties	
Longitudinal Young modulus, E_{11} (GPa) Tension	141.00
Transverse Young modulus, $E_{22}=E_{33}$ (GPa) Tension	10.00
Longitudinal tensile strength X_t (MPa)	2207
Longitudinal compressive strength X_c (MPa)	1531
Transverse tensile strength Y_t (MPa)	81
Shear strength S_{12} (MPa)	114
Ply thickness (mm)	0.13

Fatigue tests were performed at a frequency of 4 Hz, under a stress ratio, $R = 0.1$, within the load amplitudes range [4–14 kN]. The run out for the fatigue tests was fixed at 10^6 cycles. For repeatability purpose, 14 tests were performed: 8 for the bonded joints and 6 for the hybrid ones. To detect the cracks initiation, backface strain technique was used and the fatigue crack was monitored by camera. In addition, after the fatigue tests some hybrid joints were tested in order to evaluate their residual strength. The failure criteria adopted for bonded joints were the total failure/rupture of the specimen, while, for hybrid joints the fatigue test was stopped when the length of crack in the adhesive was equal to about 12 mm.

3. Results and discussion

In this section, results from the experimental tests are discussed as follows: section 3.1, static tests; section 3.2 fatigue tests.

3.1. Static tests

Fig. 2 shows the averaged load vs. crosshead displacement curve for both hybrid and bonded joints. Static tests have been carried out up to the collapse of the specimens. The comparison of the curves was performed to highlight the different structural behavior of the joints.

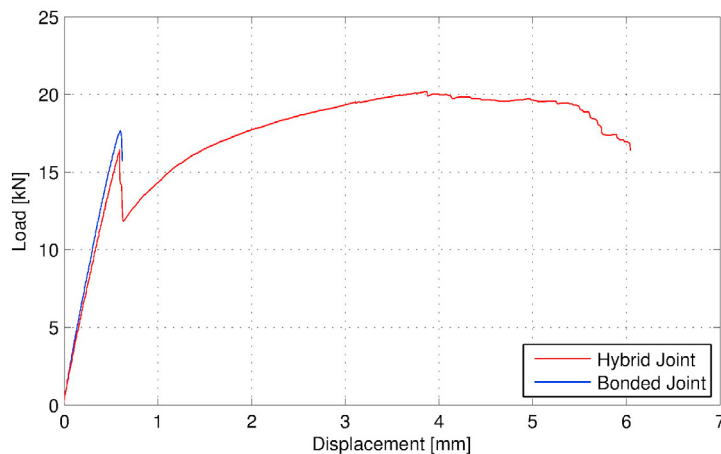


Fig. 2. Results from static tests

According to Fig. 2, the maximum load supported by hybrid joints is 15% higher than the one supported by the bonded joints. This can be attributed to the presence of the bolt. However, according to Fig. 2, the adhesive layer in

bonded joints supports a higher load than the one used in the hybrid joint, being the unique part addressed to such purpose. In this sense, by observing the first pick of the curves, it can be also noticed that from the static behavior point of view, the bolt does not provide any benefit to the joint strength. This aspect can be addressed to the fact that for the bonding a structural adhesive was used. As a result, at the beginning of the test the load is completely absorbed by the adhesive layer.

3.2. Fatigue tests

Fig. 3 shows the facility used for the fatigue test. Results related to both hybrid and bonded joints are shown in Fig. 4.

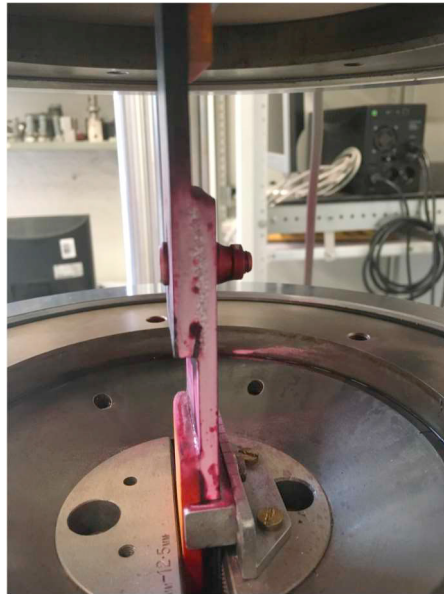


Fig. 3. Fatigue test facility.

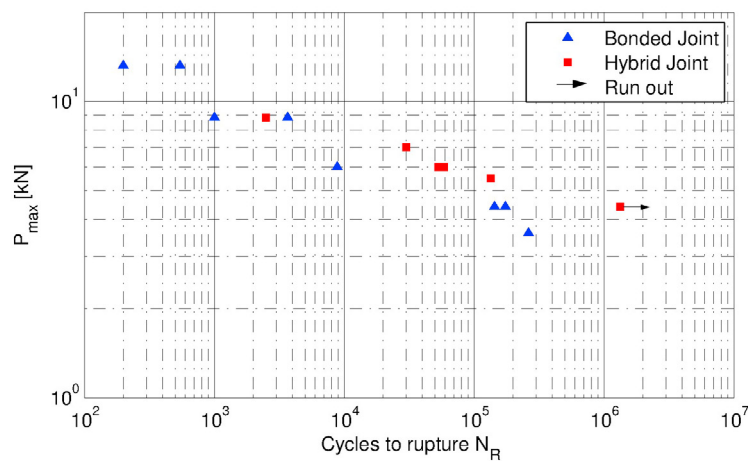


Fig. 4. Results from static tests

According to Fig.4, it appears that, for load levels higher than 8 kN, the mechanical fastener did not improve the fatigue life of the joints. Contrary, for load levels lower than 4 kN, it can be observed that the mechanical fastener improved the fatigue life of about 10 times. The crack initiation in the adhesive layer was monitored during the fatigue tests through the backface strain technique. During the tests, crack propagation was measured through the liquid penetrant technique and a proper camera (Fig. 5). Tests were stopped and specimens considered failed at the crack length of 12 mm. The run out of the tests was fixed at 10^6 cycles for all undamaged specimens.

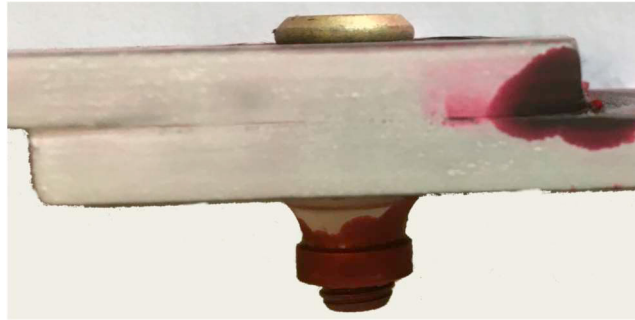


Fig. 5. Liquid penetrant testing for failed specimens.

To better understand the fatigue behavior of the hybrid joints, as aforementioned, further tests were performed to evaluate the residual strength of the specimens. Fig. 6 shows the load vs. crosshead displacement curves carried out from the tensile tests on fatigue tested hybrid joints after N_R 35000, 53000, 135000 cycles.

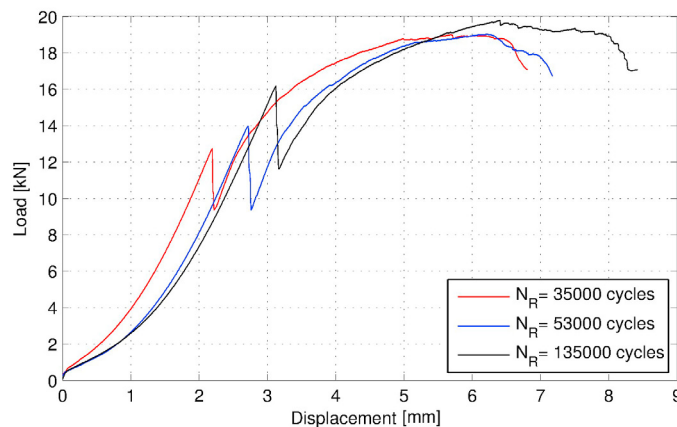


Fig. 6. Residual strength tests

From Fig. 6, the residual strength of the hybrid joints is observed to decrease as the fatigue decreases. Moreover, according to the observations, it can be stated that higher load levels introduce more severe damages in the adhesive layer.

4. Conclusions

In this paper, quasi-static tensile and fatigue tests were carried out to evaluate and compare the structural behavior of bonded and hybrid joints.

According to the results, it was observed that the maximum load supported by the adhesive layers in hybrid joints is lower than the one supported by bonded joints. Moreover, it was also noticed that the mechanical fastener did not

improve the fatigue life of the joints for load levels higher than 8 kN. Specifically, for load levels lower than 4 kN, the fatigue life of the joints increases of 10 times, almost.

During the research activities, some quasi-static tensile tests have been also addressed to evaluate the residual strength of the hybrid joints. According to the results, it was observed that the residual strength of the joints decreases as the fatigue life decreases. In addition, the higher load levels introduce more severe cracks in the adhesive layer.

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