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FATIGUE BEHAVIOUR OF CFRP/STEEL HYBRID COMPOSITES

J. Lopes[1], D. Stefaniak[2], P.P. Camanho[3], M. Freitas[4], L. Reis[5,*]

[1,4,5]IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
Av. Rovisco Pais, 1049-001 Lisboa, Portugal.
[2]DLR, Institute of Composite Structures and Adaptive Systems, Ottenbecker Damm 12, 21684 Stade, Germany
[3]IDMEC, Pólo FEUP. Rua Dr. Roberto Frias. 4200-465 Porto. Portugal.

*luis.g.reis@ist.utl.pt

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Summary: Hybrid CFRP/steel composites are a very promising solution to increase bolt bearing strength in composite aerospace structures. This paper reports the findings on the static and fatigue tests performed in composite specimens made of CFRP and steel foils and compares these results with conventional CFRP specimens. A servo hydraulic machine was used to perform fatigue tests under load control regime with R=0.05. Sinusoidal waveforms were adopted to control the load time evolution. Hybrid specimens have a considerable higher static strength than conventional CFRP and therefore their stress levels are higher in absolute values than conventional CFRP specimens. Conventional manufacturing techniques such as hand lay-up and drilling can be successfully applied to hybrid CFRP/steel composites.

1 INTRODUCTION

The assembly of composite structures in aerospace applications presents greater challenges that the assembly of metal alloy materials. This is due to several factors: The brittle nature of CFRP, the high notch sensitivity, the relative low bearing strength, the inherent anisotropy, and the dependence on lay-up configuration. Hybrid composites consisting of CFRP metallic foils are a promising solution to increase the bearing strength of composite bolted joints. Unlike GLARE this solution is aimed specifically at increasing the bearing strength. This means that the inclusion of the metallic foils is limited to the vicinity of the bolted area. The German Aerospace Agency, DLR, pioneered the hybrid concept of combining CFRP and metallic foils using Ti alloy Ti6Al4V [1], DLR and other research partners performed experimental and numerical tests of CFRP/Ti alloy [2] and an assessment of the application of this technology was performed in a spacecraft structure [3]. Titanium alloy is an expensive material. Austenitic steel, while retaining electrochemical compatibility, is far less expensive and therefore is a better overall solution than Ti alloy. The surface treatment is of paramount importance in order to assure a proper adhesion in the CFRP/Steel interface. The steel foils were subjected to a vacuum blasting surface treatment in order to improve its adhesion performance. A previous study on the inter laminar shear stress in hybrid CFRP/Steel concluded that vacuum blasting is the best suited surface treatment for steel and withstands a shear stress in the Steel/CFRP interface higher than 99% than the maximum shear stress of the CFRP/CFRP interface [4]. Up until now there are available results in the static bearing strength and inter-laminar shear stress of CFRP/Ti alloys[1], as well as inter-laminar shear stress on CFRP/Austenitic steel [4]. This paper presents two new findings: Bearing strength of CFRP/Austenitic steel and bearing fatigue response of CFRP/Austenitic steel, i.e. hybrid composites.

2 MANUFACTURE OF SPECIMENS

The specimens were manufactured in Institute of Composite Structures and Adaptive Systems of the German Aerospace Agency, DLR. The geometry of the specimens is in accordance with ASTM standard D 5961 - Bearing Response of Polymer Matrix Composite Laminates [5]. Figure 1 shows the dimensions of these specimens.

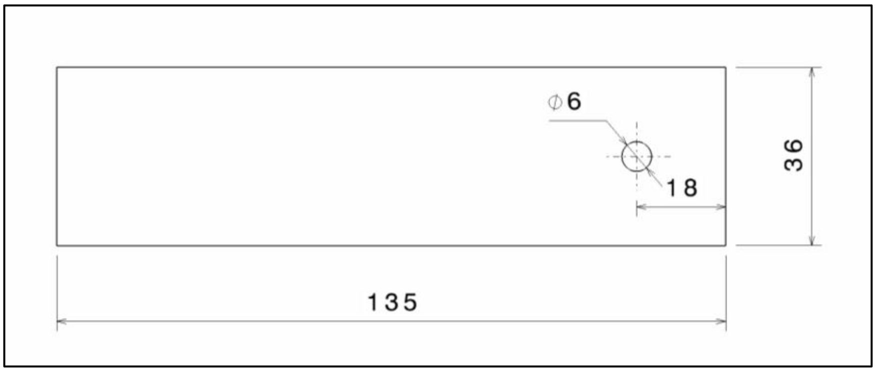

Figure 1 – Dimensions of the specimen (mm).

The CFRP material is 8552/AS4 UD prepreg from Hexcel with 134 g/m^2, a widely used CFRP in the aerospace industry. The selected austenitic steel is austenitic steel 1.4310 (X10CrNi18-8) [6]. The basic properties of these materials are given in Table 1.

The thickness of the CFPR and steel plies is 0.12 mm. The thickness of the specimens is 1.44 mm. Three different orthotropic lay-ups were tested. One reference specimen and two hybrid specimens, see Table 2:

Material	Tensile Stiffness E_1 (GPa)	Tensile Stiffness E_2 (GPa)	Density ρ (g/cm^3)
Steel 1.4310 [7]	178	178	7.9
CFRP 8552/AS4 [8]	141	10	1.58

Table 1 - Material properties.

Type of specimens	Lay-up
Reference lay-up:	$[0º / +45º / 0º / 90º / -45º / 0º]_S$
Hybrid 1	$[0º$ / (Steel) / $0º / 90º$ / (Steel) / $0º]_S$
Hybrid 2	$[0º / +45º / 0º$ / (Steel) / $-45º / 0º]_S$

Table 2 - Orthotropic lay-ups.

These lay-ups were selected due to the previous experience in this specific lay-up in static tests of hybrid CFRP/Ti alloys [2]. The quantity of specimens was 15 for the Reference lay-up Specimens and Hybrid 1 Specimens. Technical issues in the cutting of Hybrid 2 specimens limited the number of this type of specimens to 11.

Conventional CFRP manufacturing technics were used in the manufacturing of hybrid CFRP/Steel components. The specimens were prepared using standard hand lay up techniques and curing cycles as per CFRP manufacturers requirements. The specimens were manufactured from large plates that, after curing, were cut by diamond saw to the proper dimensions. The holes in the specimens were drilled using standard CFRP drilling tools. Figures 2 and 3 show a section view in the vicinity of the hole of the Hybrid 1 and Hybrid 2 specimens, respectively. Steel foils are represented in grey in Figures 2 and 3.

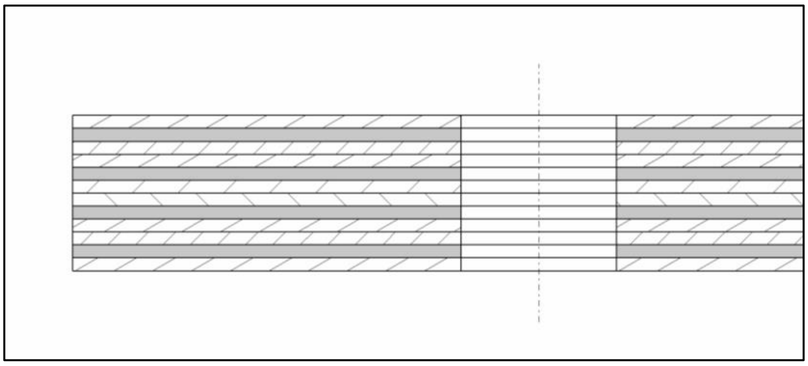

Figure 2 - Section View of the Hybrid 1 specimen $[0º$ / (Steel) / $0º / 90º$ / (Steel) / $0º]_{S.}$

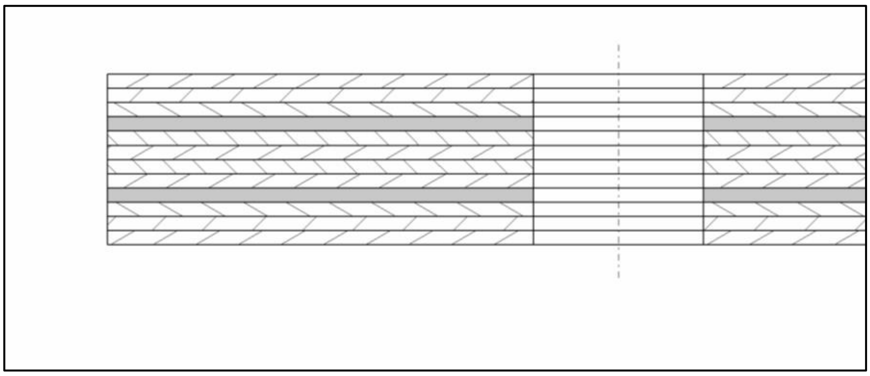

Figure 3 - Section View of the Hybrid 1 specimen. $[0 / +45º / 0$ / (Steel) / $-45 / 0]_{S.}$

3 STATIC TESTS

Static tests were performed using an Instron 3489 testing machine with a capacity of 50 kN. The speed of the test was set at 1 mm/min. Figure 4 shows the specimen fixed in the lower part of the testing machine. To simulate the effect of a bolt a fixture with a pin that passes through the hole is installed in the upper part of the specimen. The pin works in double shear. Two specimens of each type of specimens were tested. The diameter of the pin is ø5.9mm which means a clearance between the hole and pin of 0.05mm in radius. The tests were ended up when the measured displacement reached 8mm. Figure 5 shows the plots of bearing response of all the tests of the three types of specimens tested.

Figure 4 - Specimen fixed in the lower end with pin in double shear insert.

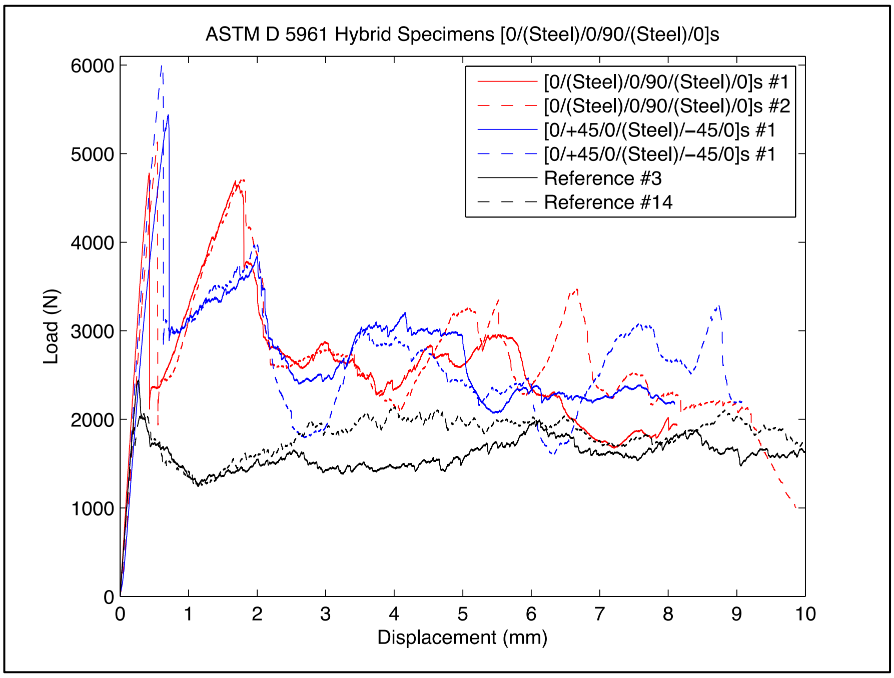

Figure 5 – Bearing response of the reference specimens.

Figures 6 and 7 show a reference specimen and a hybrid specimen after being tested, respectively. Note the crushing of the steel foils in the hybrid specimen.

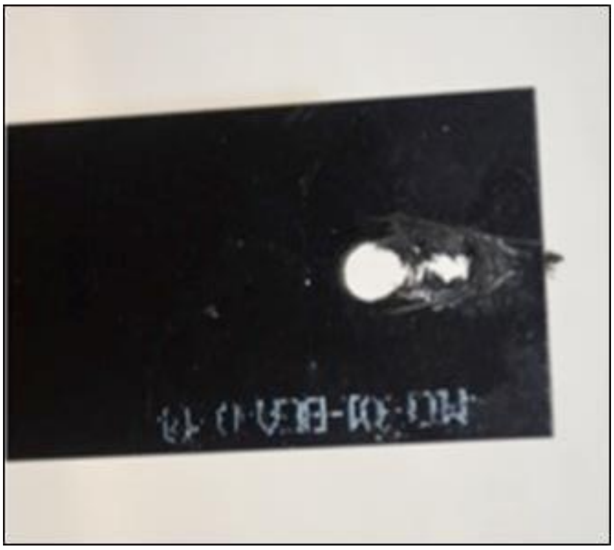

Figure 6 – Reference specimen after testing.

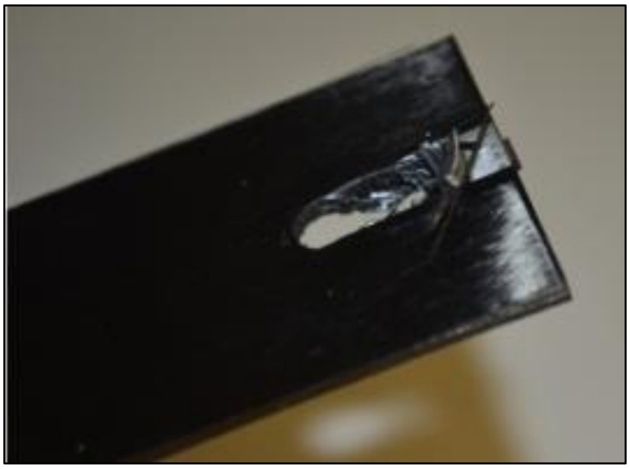

Figure 7 – Hybrid specimen after testing.

Based on the peak load and on the geometry of the specimens the bearing stress, σ^{br}, can be calculated.

$$\sigma^{br} = \frac{P}{D.h} \tag{1}$$

Where P is the peak load in Newton, and D and h are the diameter and thickness of the specimens in mm, respectively. Table 3 presents the maximum load of all the tests and the maximum bearing stress.

Specimens		Maximum load (kN)	σ^{br} (MPa)
Reference Specimens	#3	2.44	282.78
	#14	2.06	239.39
Hybrid 1 specimens	#1	4.78	553.31
	#2	5.13	593.90
Hybrid 2 specimens	#1	5.43	629.50
	#2	6.01	696.04

Table 3 **-** Summary of the bearing response tests.

4 FATIGUE TESTS

The fatigue tests were performed in a servo-hydraulic testing machine Instron 8874 with 25 kN of capacity. The stress ratio was set at R=0.05 with a sinusoidal waveform, controlled in load. Frequency of the tests was 6 Hz.

The peak loads obtained in the static tests were used as guideline for the stress levels that would be applied on the specimens. Ideally the stress levels would be percentages of the maximum stress obtained in static tests. This proved difficult to implement in CFRP specimens. At a given stress level these specimens would either fracture or continue to carry on supporting the loads with no apparent damage. For this reason the stress levels were set at a decreasing intensity, see Table 4. Figure 8 shows the same fixture used in the static tests installed in the servo-hydraulic testing machine for fatigue tests. The results of the tests are presented in Table 4.

Figure 8 – Specimen in the fatigue testing machine.

Specimens	Maximum force (N)	Minimum force (N)	Mean force (N)	Alternating Force	Cycles
Reference lay-up	2400	120.00	1260.00	1140.00	2400
	2200	110.00	1155.00	1045.00	2200
	2300	115.00	1207.50	1092.50	2300
	2240	112.00	1176.00	1064.00	2240
	2235	111.75	1173.38	1061.62	2235
	2230	111.50	1170.75	1059.25	2230
Hybrid 1	4850	242.50	2546.25	2303.75	7612
	4790	239.50	2514.75	2275.25	8771
	4650	232.50	2441.25	2208.75	9045
	4100	205.00	2152.50	1947.50	10126
	3850	192.50	2021.25	1828.75	13446
	3500	175.00	1837.50	1662.50	17342
	3350	167.50	1758.75	1591.25	19234
Hybrid 2	5400	270.00	2835.00	2565.00	128
	5000	250.00	2625.00	2375.00	9816
	4800	240.00	2520.00	2280.00	12843
	4700	235.00	2467.50	2232.50	60401
	4500	225.00	2362.50	2137.50	99942
	4400	220.00	2310.00	2090.00	108463
	4200	210.00	2205.00	1995.00	218421
	4000	200.00	2100.00	1900.00	221465

Table 4 - Results of the fatigue tests.

The S-N diagram for all the specimens based on the results of Table 4 is presented in Figure 9. The dashed lines represent the equation of logarithmic regression for each type of specimens. The regression equation and the correlation coefficients are presented in Table 5.

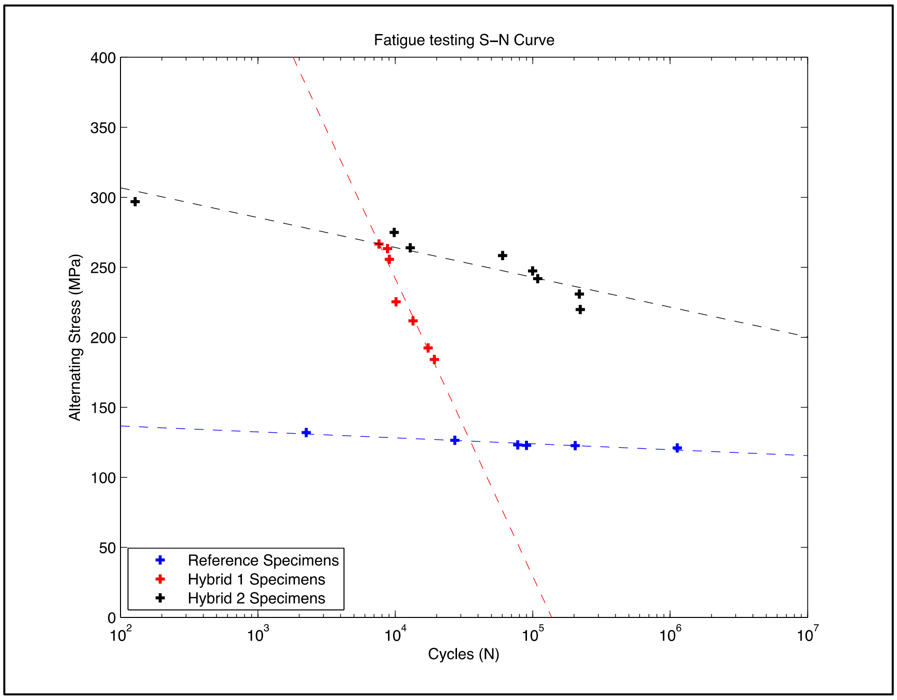

Figure 9 - S-N Diagram of the fatigue specimens.

	Regression equation	Correlation coeficient
Reference lay-up specimens	y=-1.84ln(x)+145.15	$R^2 = 0.92038$
Hybrid 1 specimens	y=-92.31ln(x)+10.9	$R^2 = 0.94834$
Hybrid 2 specimens	y=-9.24ln(x)+349.30	$R^2 = 0.86494$

Table 5 - Regression equations and correlation coefficients.

5 DISCUSSION

The static tests confirm that hybrid CFRP/Steel specimens have a maximum bearing strength much higher than the reference specimens. Similar results were already observed when testing the bearing strength of CFRP/Ti alloy [2]. Two other important evidences can be observed:

A higher content of steel does not ensure by itself a higher bearing strength. Hybrid 2 specimens have 2 steel foils and have a higher bearing strength than Hybrid 1 specimens that have 4 foils. This is due to the fact that the 90º plies were replaced by steel foils in the Hybrid 2 specimen, thus enabling to carry more load.

Another important aspect is the fact that in the case of the hybrid specimens after the peak load the load increases again for a second peak. This may occur due to the hardening of the steel when is subjected to plastic strain. This is a very interesting aspect. In the case of the Hybrid 1 specimens this second peak is approximately 90% of the first peak.

The fatigue tests of the reference specimens confirm the low sensitivity to fatigue typical of CFRP laminates.

The hybrid specimens have more interesting results:

Both type of hybrid specimens sustain a higher alternating stress that reference specimens. This was already predictable by the results of the static tests. In the case of the Hybrid 1 specimens with its 4 steel foils the metallic behaviour is dominant over the CFRP behaviour. Thus the sharp negative slope compared with the almost flat slope of the reference specimens. The Hybrid 2 specimens have an even more interesting behaviour: Their highest endurance stress is close the highest endurance stress of the Hybrid 1 specimens but these specimens, with their lower content of steel, have a lower sensitivity to fatigue, typical of pure CFRP. It shows that a lower content of steel is the most balanced solution for excellent fatigue performance.

6 CONCLUSIONS

The inclusion of steel foils in CFRP laminates enable an outstanding increase, over 100% in the Hybrid 2 case, of the bearing strength when compared with the reference CFRP. The sustained load of hybrid CFRP/Steel after full damage is in average above the highest load achieved by the pure CFRP plies.

The placement of the steel foils should be where CFRP plies are most likely to fail in order to maximize the benefits of hybridization.

The hardening of steel enables a rise in the load after the first peak load. This second peak is very important. It enables to carry a significant amount of load, higher than the peak load of pure

CFRP, with a significant amount of displacement. This property can be used in aerospace applications where critical structures have to sustain a significant amount of plastic deformation .

Hybrid CFRP/steel composites have excellent fatigue properties. Although more sensitive to fatigue than pure CFRP, hybrid CFR/Steel laminates have a higher endurance. As in the case of the static tests a moderate amount of steel content is the most balanced option: Higher endurance stress with moderate sensitivity to fatigue.

With these findings two preliminary design guidelines for hybrid CFRP/Steel composites can be proposed:

i. Steel foils should be placed where the CFRP is more likely to fail,
ii. Moderate amount of steel content should be used in hybrid composite joints.

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