Short-beam shear fatigue life assessment of thermally cycled carbon–aluminium laminates with protective glass interlayers

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Received: 19 October 2020 / Revised: 4 January 2021 / Accepted: 8 January 2021 / Published online: 11 March 2021
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Abstract

Fibre metal laminates (FMLs) are attractive construction materials, especially for use in aerospace and transport facilities. Throughout their service life, thin-walled structures made of FMLs are exposed to static and dynamic loads, as well as corrosion and the unfavourable influence of environmental conditions. The paper presents an experimental analysis of the combined mechanical and environmental long-term behaviour of carbon-based fibre metal laminates and their variants with protective glass layers. The Al alloy/CFRP and Al alloy/GFRP/CFRP laminates in a 3/2 configuration were used. The tested laminates were subjected to 1500 thermal cycles with a temperature range of 130 °C. The static and fatigue interlaminar shear strengths were tested before and after thermal conditioning. It was shown that the stable stiffness reduction in the tested laminates was observed with increasing fatigue cycles, due to the progressive fatigue damage accumulation. The thermally cycled laminates feature slightly smoother stiffness loss, while a more rapid decrease was observed in thermally untreated laminates. Moreover, the fatigue life of the tested laminates subjected to thermal cycling revealed nine times fewer fatigue cycles of laminates with glass protectors after thermal cycles in comparison to the laminates not subjected to thermal cycling.

Keywords FML · GFRP · CFRP · Fatigue · ILSS · Thermal shock

1 Introduction

Fibre metal laminates (FMLs) are attractive construction materials, especially for use in aerospace and transport facilities. The first manufactured GLARE® and CARALL® laminates became the points of reference for developing the scientific basis for designing the properties of FMLs. Throughout their service life, thin-walled structures made of FMLs are exposed to static and dynamic loads, as well as corrosion and the unfavourable influence of environmental conditions. Due to this, in addition to typical mechanical tests, the process of designing primary and secondary structures must include corrosive, thermal and thermo-mechanical fatigue tests.

The properties of fibre metal laminates depend on those of the constitutive metal and composite materials. However, the final properties of an FML are influenced by a

large number of additional aspects. Besides the manufacturing technology, which may generate additional stresses in operating temperature, the adhesive joint between metal and composite serves a particularly important function. Insufficient critical strain energy release rate of the adhesive metal/composite joint may result in the propagation of delamination, leading to the premature failure of the structures, e.g. when subjected to compression or fatigue. Generally, the mechanical properties of the adhesive joint may be traditionally evaluated by standard fracture toughness tests typically in the opening, shearing, or mixed shearing/opening mode. However, in recent years, short-beam shear (SBS) tests are also increasingly being used as mechanical tests, especially for comparative purposes. The previous example of using interlaminar shear strength (ILSS) to compare FML properties was presented by Sinmazçelik et al. [1] in a review paper from 2011. Kotik and Perez-Ipiña [2] employed the SBS test to obtain the information about quasi-static and fatigue interlaminar shear responses of a commercial FML. Liu et al. [3] showed that lay-up configuration of glass/epoxy layer strongly affected load–deflection response, especially the failure load, and corresponding failure mode. Bellini et al. [4] studied the influence of both composite/metal interface

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and layer thickness on ILSS in Al/CFRP laminates with extra polymer interlayers. They concluded that the most influencing factor was the presence of the structural adhesive, while the number of metal sheets was unaffacting.

As recently found, the adhesive connection of 2024-T3 aluminium alloy with glass fibres is in general characterized by a higher critical strain energy release rate than an adhesive connection with carbon fibres in both static [5] and fatigue [6] loadings, even though the same type of epoxy matrix is used. Nevertheless, the carbon-fibre-reinforced fibre metal laminates (CARALL type) are characterized by a significantly higher strength [7] and fatigue resistance [8], while having a lower density than glass-fibre-reinforced GLARE used in aircraft structures. However, the direct application of carbon fibres combined with an aluminium alloy in an aircraft structure is still considered to be risky due to the galvanic interaction between the aluminium alloy and carbon fibres. Liu et al. [9] and Peng et al. [10] confirmed the establishment of a galvanic couple and associated corrosion when the aluminium alloy is coupled to the CFRP composite. For this reason, in recent years, some attempts have been made to separate carbon fibres from an aluminium alloy by introducing additional dielectric layers as structural adhesive [4], prepreg resin [7], glass fibres [11] and glass fibres with adhesives [12], or other materials, such as rubber [13], also replacing an aluminium alloy with titanium [14].

It should be noted that even though the mechanical properties of hybrid carbon-fibre-reinforced laminates with added dielectric layers are rather promising, the long-term behaviour of those materials is investigated rather rarely. The influence of thermal cycling on the properties of GLARE with an external heating source was investigated by Müller et al. [15]. As the authors concluded, external heating and cooling as applied to GLARE, (with a temperature range of 120 °C) increased their interlaminar shear strength by about 4% due to epoxy ageing. As a result, the aged matrix exhibited an increased stiffness and strength when compared to the reference material. Park et al. [16] noted a 9–18% decrease of interlaminar shear strength of GLARE after 1500 thermal cycles. Khosravani and Weinberg [17] studied the influence of accelerated ageing on mechanical strength of GFRP/sandwich joint and observed the decrease of properties with adhesive failure. Garcia-Moreno et al. [18] studied the effect of thermal ageing on the impact damage resistance and tolerance of carbon-fibre-reinforced epoxy laminates. They concluded that thermal ageing below the glass transition temperature for short periods of time leads to a process called post-curing which consolidates the CFRP laminate improving the adhesion between the fibres and the matrix. On the other hand, Jakubczak et al. [19] found that the thermal cycling of CARALL laminates does not affect the value of interlaminar shear strength, although some differences in fractographical microstructural analyses were reported. Da

Costa et al. [20] also reported the limited influence of thermal cycles up to 2000 cycles of aluminium/glass laminates on shear strength.

Knowledge of the thermal and mechanical fatigue behaviour of components and hybrid laminates provides the ability to predict fatigue life and crack growth rates. The effects of cyclic loading on the fatigue of CFRP are detailed in several papers and collated in some review papers, e.g. by Alam et al. [21]. Zhou et al. [22] proposed the progressive fatigue damage modelling of fibre-reinforced fibre-reinforced composite based on fatigue master curves. A method to predict the fatigue life and residual strength of composite materials subjected to variable amplitude loadings was proposed by D'Amore and Grassia [23]. Alderliesten [24], Homan [25] and others proposed analytical models of fatigue crack initiation and propagation in FMLs based on experimental results. Prediction methodologies for fatigue crack behaviour have been developed and verified for different loading [26, 27], different stress cycles and cycle characteristics [28], at various temperatures [29], etc. Therefore, when designing new hybrid laminates to operate under varying thermal and mechanical loads, it is necessary to expand the database of their properties as well as understanding the behavior under various load conditions (thermal, mechanical).

Taking assume above the aim of this paper was to analyse the combined mechanical and environmental long-term behaviour of carbon-based fibre metal laminates and their variants with protective glass layers. For this reason, laminates were subjected to 1500 thermal cycles with a temperature range of 130 °C (from – 50 to + 80 °C), with subsequent mechanical fatigue loading until laminate failure. Through this, the combined environmental and mechanical long-term behaviour was investigated on CARALL with an additional dielectric glass fibre with two fibre orientations, and, for comparative purposes, on conventional carbon fibre-reinforced aluminium laminates.

2 Materials and methods

2.1 Materials

The studied laminates were GFRP and CFRP laminates containing layers of aluminium alloy. The thickness of aluminium alloy grade 2024-T3 sheets was 0.3 mm. The surface of the sheets was coated with the organic–inorganic hybrid sol–gel 3 M Surface Pre-Treatment AC 130-2 two-component formulation (3 M, USA) as an adhesive film. See earlier publication for detailed information on the method of metal surface preparation and the used primer [12].

Carbon-fibre-reinforced epoxy prepreg (NTPT, Switzerland) with a fibre weight of 200 gsm and a ply thickness of about 0.2 mm and ThinPly-type glass fibre/epoxy prepreg

(NTPT, Switzerland) with a fibre weight of 40 gsm and a layer thickness of 0.04 mm were laid in the 0° and 90° directions in sequences, as shown in Fig. 1. Sample notation is presented in Table 1. When an ultra-thin glass layer is laminated in the 0° direction, i.e. in accordance with the direction of carbon fibres, local contact of carbon fibres with aluminium may occur due to the migration of fibres during the autoclave process [19]. Therefore, a perpendicular GFRP layer was also used as an effective barrier to avoid carbon and glass fibre interpenetration, while the GFRP layers were laminated in a perpendicular direction. CARALL in a 3/2 configuration was used as the reference material.

Fig. 1 The configurations of the tested laminates

The panels were manufactured using the autoclave method with vacuum bag assistance (SCHOLZ Maschinenbau autoclave, Germany). The curing involved a two-step temperature process (80 °C for 1 h and 150 °C for 4 h). The heating and cooling rates were 1.2 °C/min. The pressure was 0.6 MPa and the vacuum was 0.02 MPa throughout the process.

The panels were cut into short-beam shear (SBS) samples using a water jet. The average sample size was 20 × 10 × 2.35 mm.

2.2 Methods

To assess the influence of glass layer configuration on mechanical properties under variable load conditions, a test methodology was developed, including thermal shocks and cyclic bending load.

Thermal shocks were carried out in an environmental chamber (Binder MKFT type, Germany) according to the scheme shown in Table 2 and in Fig. 2a. The samples in the environmental chamber are shown in Fig. 2b. The temperature was changed from − 50 to + 80 °C. In general, this range of temperature is typical in aircraft operating. Used thermal conditions can be compared to real conditions for aircraft structures, e.g. fuselage during standard operation (ascents and descents − 55 °C to + 70 °C, also anti- or de-icing − 25 °C to + 80 °C) [15, 18, 20]. The detailed course of this research is described in other works [12, 19].

Strength tests were performed as quasi-static and fatigue tests before and after thermal shocks. The short-beam sample

Table 1 Notation of samples

Notation	Conditions	Sample configuration
Al/CFRP		
NC	No shocks	Al/CFRP (0) ₄ /Al/CFRP(0) ₄ /Al (Carall 3/2)
SC	After shocks	
Al/G(0)/CFRP		
NG0C	No shocks	Al/GFRP(0)/CFRP(0) ₄ /Al/CFRP(0) ₄ /GFRP(0)/Al
SG0C	After shocks	
Al/G(90)/CFRP		
NG90C	No shocks	Al/GFRP(90)/CFRP(0) ₄ /Al/CFRP(0) ₄ /GFRP(90)/Al
SG90C	After shocks	
Mechanical properties of tested Al/CFRP laminate* and two other types**		
Tensile strength: 1207 MPa ± 99 (ASTM D3039)		
Young modulus: 94 GPa ± 3 (ASTM D3039)		
Poisson ratio: 0.28 ± 0.01 (ASTM D3039)		
Compressive strength: 834 MPa ± 6 (ASTM 3410)		

*Based on authors own research

**Because of the small thickness of protective glass layers (0.04 mm) and similar glass fibres strength (high strength S2 type of glass) compared to carbon fibres, the mechanical properties in two other types of laminates change only in low range contained in the standard deviation of properties laminate Al/CFRP

Table 2 Parameters of thermal cycles

Cycle no	Cycle name	Time (min)	Temperature (°C)	Heating/cooling rate (°C/min)
0	Start	14.2	RT ^a → -50	5
1	Stabilization	5	-50	—
	Heating	26	-50 → 80	5
	Stabilization	5	80	—
	Cooling	26	80 → -50	5
2	Stabilization	5	-50	—
	Heating	26	-50 → 80	5
	Stabilization	5	80	—
	Cooling	26	80 → -50	5
etc. until				
1500	Stabilization	5	-50	—
	Heating	26	-50 → 80	5
	Stabilization	5	80	—
	Cooling	26	80 → -50	5
—	Stop	14.2	-50 → RT	5

^aRoom temperature 21 °C

bending method according to the EN ISO 14130:1997 standard was used [30]. Interlaminar shear strength (ILSS) was determined using the following equation [30]:

$$\tau = \frac{3}{4} \frac{P}{bh} [\text{MPa}], \quad (1)$$

where P is the maximum load [N], and b and h are the width and thickness of the specimen [mm], respectively.

A three-point bending device was used. The radii of support rollers and the loading member were 2 mm and 5 mm, respectively. A span-to-thickness ratio of 5.0 was used. The quasi-static tests were performed on a Shimadzu AG-X Plus mechanical testing machine (Japan) with the crosshead speed of 1.3 mm/min.

The fatigue tests were performed using the INSTRON 8801 Fatigue Testing Systems 100 kN (UK) machine with an additional load cell INTERFACE 1010ACK-5KN-B (USA) with a 5 kN load capacity. The specimens were force-driven tested at a 5 Hz loading frequency. The maximum load level in fatigue tests was specified as 65% of the static ILSS. According to Kotik and Perez-Ipina [2] this loading range is recommended to obtain stable progressive fatigue damage of the short-beam shear specimen and, as a result, a stable stiffness decrease until the final failure. Fatigue tests were conducted until the stiffness of the specimen degraded below 20% of its initial value (S_{ini}). Ten and three specimens for each configuration were tested in quasi-static and dynamic bending tests, respectively. The scheme and the real view of the ILSS test are presented in Fig. 3, while the test procedure is presented in Fig. 4.

3 Results and discussion

3.1 Static interlaminar shear

The static bending test was carried out to determine the maximum shear stress of laminates before and after thermal shocks. The stress values were necessary to establish fatigue test parameters.

Table 3 and Fig. 5 contain the averaged test results. Laminates containing a layer of glass fibre showed a slight tendency to ILSS decrease due to thermal shocks. The CAR-ALL type laminate showed an increase in stress after 1500 thermal cycles.

Although there is a slight tendency to ILSS change, statistical analysis with the HSD Tukey test did not show statistically significant differences between the calculated ILSS values (see Table 4), with the exception of SC samples.

Similar trends have been observed in authors previous studies for laminates with a different method of aluminium

Fig. 2 Scheme of thermal cycles (a) and the samples inside the environmental chamber (b)

Fig. 3 The scheme (a) and sample view (b) of ILSS static and fatigue tests

Fig. 4 The scheme of the full test procedure

surface preparation [12, 19] and in hygrothermal conditions by da Costa [20]. Significant effects of thermal shocks on GLARE [15, 31–33] and CARALL [34, 35] laminates were only observed after more than 10,000 thermal cycles. The

lack of significant difference in interlaminar shear strength of the tested laminates results from the very low thickness of glass layers and effectively limiting degradation of the metal/composite interface. It is known that the interlaminar shear strength of FML is controlled by the interface between the metal and the composite layer [20, 35]. Stresses resulting from thermal shocks generally reach the maximum value at the fibre–matrix interfaces and boundaries between adjacent composite layers of different fibre orientations [35]. Moreover, the epoxy matrix may become plasticized or swell, reducing ILSS [36, 37]. In good metal/composite interfacial adhesion systems, these effects are not significant. The used organic–inorganic hybrid sol–gel primer belonging to the second-generation coatings ensures a high corrosion resistance by creating a dense Si-O-Si network and providing high adhesion to metal surfaces, owing to the formation of covalent Me-O-Si bonds [38, 39]. The observed increase of ILSS in Al/CFRP and the constant value of ILSS in Al/G/CFRP after thermal shocks are probably due to the reaction between the metal, epoxy and primer, leading to an increase in bond strength in the interface area [40]. It should be also noted, that the formula used for the determination of ILSS is based on homogeneous beam theory, which predicts a continuous, parabolic distribution of the shear stress, with a maximum on the neutral plane of the laminated beams [41]. In the current specimens, the above-mentioned formula yields the maximum stress value, which occurs in the middle of the aluminium layer. Despite in the literature, more advanced mechanical models can be found [41], for instance, Classical Sandwich Theory, for the comparisons of the interface durability before and after any processing, the primary formula, Eq. (1) yields reasonable results [2, 3, 5, 7, 41, 42]. It is also worth mentioning that, the investigated metal/composite interfaces are placed with a very slight offset from the neutral plane of 0.15 mm, meaning that the real ILSS value could be insignificantly lower than measured. However, as

Table 3 Interlaminar shear strength of laminates before and after thermal shocks

Sample	$P_{\max}$ (N)	ILSS (MPa)	Sample	$P_{\max}$ (N)	ILSS (MPa)
NC	2033 $\pm$ 102 CV = 5.0	70.33 $\pm$ 3.24 CV = 4.6	SC	2353 $\pm$ 111 CV = 4.7	76.79 $\pm$ 3.32 CV = 4.32
NG0C	2243 $\pm$ 119 CV = 5.3	71.18 $\pm$ 3.1 CV = 4.35	SG0C	2115 $\pm$ 110 CV = 5.2	68.31 $\pm$ 3.29 CV = 4.82
NG90C	2270 $\pm$ 82 CV = 3.6	72.65 $\pm$ 2.06 CV = 2.83	SG90C	2155 $\pm$ 93 CV = 4.3	68.52 $\pm$ 2.9 CV = 4.29

CV sample coefficient of variation, in percent

Fig. 5 Interlaminar shear strength of laminates before and after thermal shocks **Table 4** Result of HSD Tukey test for ILSS

	70.33 {1}	71.18 {2}	72.65 {3}	76.79 {4}	68.31 {5}	68.52 {6}
NC {1}		0.991	0.585	0.001	0.714	0.796
NG0C {2}	0.991		0.905	0.003	0.348	0.430
NG90C {3}	0.585	0.905		0.055	0.040	0.057
SC {4}	0.001	0.003	0.055		0.000	0.000
SG0C {5}	0.714	0.348	0.040	0.000		1.000
SG90C {6}	0.796	0.430	0.057	0.000	1.000	

long as the laminate general layup (fiber metal laminate with 3/2 configuration), global laminate thickness, as well as the offset of investigated metal/composite interface from the neutral plane is 0.15 mm and remains on a constant level, the obtained results of static ILSS, as well as the ILSS values after thermal cycling, are comparable in terms of the mechanical response of the beam.

3.2 Fatigue life

After a series of preliminary tests, and taking into account the results of Kotik and Perez-Ipina [2] concerning the behaviour of a short-beam shear specimen subjected to mechanical fatigue, the fatigue tests were carried out at an initial stress level of 65% of the shear stress obtained from the quasi-static test. Due to the very slight differences in the values of interlaminar shear strength (as an average in

Table 3) the fatigue test after environmental conditioning was performed at constant stress levels for the global specimen population. However, due to the differences of specimen thickness, caused by the different layups, the maximum forces were adjusted to each specimen to obtain constant interlaminar shear stress (46.3 MPa) regardless of the layup configuration. The geometry and resulting force levels as well as the S_{ini} initial stiffness value (determined after 100 fatigue cycles) are specified in Table 5.

Fatigue tests were performed until the stiffness decreased below 20% of their initial value. The fatigue test results for reference materials before thermal shocks and after thermal shocks are shown in Fig. 6.

As can be seen in Fig. 6, in the first stage of mechanical fatigue life (from 1 to 103 cycles), the material's cyclic hardening was observed. The normalized laminate stiffness (S/S_{ini}) increased up to 10% for all of the tested specimens. A

Table 5 SBS fatigue test parameters

h (mm)	b (mm)	$\tau_{\max}$ (65%) (MPa)	$P_{\max}$ (N)	$P_{\min}$ (N)	ΔP (N)	δ at $P_{\max}$ (mm)	δ at $P_{\min}$ (mm)	$\Delta\delta$ (mm)	$S_{ini} \Delta P/\Delta\delta$ (N/mm)
NC									
2.32	9.93	46.3	1423	142	1281	27.501	27.407	0.0936	13,692
2.29	9.88	46.3	1398	140	1258	27.504	27.414	0.0891	14,125
2.32	9.93	46.3	1420	142	1278	27.512	27.425	0.0870	14,691
NGOC									
2.37	9.88	46.3	1443	144	1299	27.681	27.591	0.0902	14,397
2.35	9.89	46.3	1435	144	1292	27.594	27.508	0.0864	14,946
2.37	9.88	46.3	1444	144	1299	27.572	27.487	0.0852	15,243
NG90C									
2.42	9.93	46.3	1482	148	1333	27.490	27.398	0.0916	14,561
2.38	9.88	46.3	1452	145	1307	27.568	27.485	0.0832	15,709
2.39	9.94	46.3	1464	146	1318	27.557	27.467	0.0897	14,697
SC									
2.34	9.90	46.3	1428	143	1285	27.602	27.511	0.0910	14,130
2.36	9.94	46.3	1449	145	1304	27.584	27.502	0.0819	15,931
2.35	9.92	46.3	1440	144	1296	27.603	27.510	0.0925	14,001
SG0C									
2.45	9.90	46.3	1499	150	1349	27.493	27.399	0.0945	14,276
2.45	9.92	46.3	1501	150	1351	27.508	27.419	0.0892	15,145
2.41	9.92	46.3	1476	148	1329	27.616	27.507	0.1093	12,162
SG90C									
2.41	9.94	46.3	1477	148	1329	27.579	27.491	0.0887	14,982
2.40	9.95	46.3	1475	148	1328	27.609	27.487	0.1220	10,883
2.41	9.94	46.3	1480	148	1332	27.528	27.431	0.0972	13,700

similar increase of the specimen stiffness of the short-beam shear specimens could be explained by the cyclic strain hardening of the 2024-T3 aluminium alloy. As described by Calabrese and Laird [43], the accumulation of dislocations, as well as their interaction with precipitations in two-phase alloys (in this case 4% copper and 1% magnesium were alloying elements), may significantly increase material stiffness subjected to cycling loading. After initial stiffness gain, a stable stiffness reduction was observed in tested laminates, due to the progressive fatigue damage accumulation. In the last phase of the specimens' fatigue life, a sudden stiffness drop was observed in every tested layup. An analysis of the stiffness history of thermally cycled laminates with reference materials demonstrates that thermally cycled laminates seem to be characterized by a slightly smoother stiffness loss, while a more rapid decrease was observed in thermally untreated laminates. The initial stiffness of the specimens subjected to thermal cycling and of the reference materials is specified in Table 6.

Comparing resistance to thermo-mechanical fatigue, as a function of the layup configurations, it may be observed that the thermal cycling caused a slight decrease of specimen stiffness in laminates with additional glass fibres in

both 0° and 90° fibre orientations (− 7% and − 12% respectively), while some additional hardening was observed in the laminate reinforced only by carbon fibres (+ 4%). A similar increase (+ 4%) of ILLS was observed by Müller et al. [15] in static SBS tests performed on GLARE. Müller et al. [15] explain this effect by the ageing of epoxy, which increases its stiffness and, as a result, also leads to the strengthening of the fibre metal laminate. Similarly, Li et al. [32] observed an increase in the static tensile and bending strength of the FMLs after thermal fatigue cycling due to the advantageous ageing behaviour and the resulting hardening of the aluminium–lithium layer. Kubit et al. [44] observed a decrease in stiffness and ILSS after the thermal cycling of fibre metal laminate made of prepregs with twisted yarn and aluminium alloy 2024-T3. Also, Hagenbeek et al. [31] observed a significant (in the range of 10–30%) decrease of ILSS after long-term thermal cycling of a fibre metal laminate reinforced by glass fibres. In the current research, also a similar significant decrease of stiffness and static ILSS (in the range of 7–12%) was observed in laminates with additional layers of glass fibres. On the other hand, Costa et al. [20] evaluated the effect of thermal-shock cycles (max. 2000 cycles) with temperature variations between − 50 and + 80 °C on

Fig. 6 Stiffness vs. fatigue cycles before (a) and after (b) thermal shocks

the mechanical properties of Al/GFRP/epoxy adhesive tape laminates and observed that the thermal-shock cycles did not result in significant microstructural changes and interlaminar shear strength of the FML.

In analyzing the fatigue life of the tested materials (fatigue number up to final failure or 80% stiffness loss), also in this case significant strengthening was observed in laminates reinforced only by carbon fibres. Although the stiffness of laminates increased rather slightly, the fatigue life of the corresponding laminate subjected to thermal cycling (material SC) withstood almost nine times more fatigue cycles than the reference materials (material NC).

The carbon-fibre-reinforced FMLs, which after thermal shocks had the highest ILSS, were subjected to relatively lower fatigue loads than the other layups. This may be the reason for the higher SBS fatigue life obtained. However, maintaining specified stress at a constant level for both thermally cycled and reference specimens is rational, since the loads applied under the real loading conditions do not decrease in the operating conditions (e.g. in the aircraft industry), but remain at a constant, designed level. Although an increase in fatigue strength was observed for laminates reinforced only with carbon fibres, the thermal cycling of fibre metal laminates reinforced by mixed carbon and glass

Table 6 Initial stiffness of short-beam shear specimens before and after thermal shocks

Initial stiffness (S_{ini}) $\Delta P/\Delta \delta$ (N/mm)					
	1	2	3	Mean	Change
Before thermal shocks					
NC	13,692	14,125	14,691	14,169	Reference
NG0C	14,397	14,946	15,243	14,862	Reference
NG90C	14,561	15,709	14,697	14,989	Reference
After 1500 thermal shocks					
SC	14,130	15,931	14,001	14,687	+
SG0C	14,276	15,145	12,162	13,861	–
SG90C	14,982	10,883	13,700	13,188	–

Table 7 Fatigue life of short-beam shear specimens before and after thermal shocks

Fatigue cycles (cycles)					
	1	2	3	Geometric mean	Change
Before thermal shocks					
NC	28,900	19,100	9900	17,614	Reference
NG0C	82,000	226,800	57,800	102,438	Reference
NG90C	108,900	137,800	74,300	103,694	Reference
After 1500 thermal shocks					
SC	125,200	297,100	129,400	168,842	+
SG0C	11,400	16,400	2700	7962	–
SG90C	21,000	6900	32,000	16,675	–

fibres (regardless of fibre orientation) caused heavy deterioration of their fatigue life. The results for fatigue life are presented in Table 7 and Fig. 7.

A similar number of fatigue cycles to failure (22,000 fatigue cycles – geometrical average) of non-thermally cycled fibre metal laminates were observed by Kotik and Perez-Ipina [2] in GLARE loaded by a shear stress amplitude with a magnitude of 23.4 MPa. For the specified stress

levels, the authors observed stable and repetitive fracture mechanisms, where the cracks formed in the middle of the span in the bottom aluminium layer. Although the order of magnitude of fatigue cycles is similar to Kotik and Perez-Ipina [2] results, some dispersion of the obtained fatigue life results have been observed. A possible origin of the dispersion of results for different tested layup configurations is the existence of differences in laminate thickness. Although the thickness differences in tested laminates were very slight (thickness, t , Table 5), Liu et al. [3] showed that the span-to-thickness ratio in an SBS test based on a three-point-bending test is crucial for the resulting ILSS value, by changing failure mode from shear-dominant for a low span-to-thickness ratio (about $s/t = 5$) to bending-dominant for a high span-to-thickness ratio ($s/t = 10$). Therefore, at the span remaining at a constant level, ($s = 10$ mm) even minor differences in laminate thickness would change the span-to-thickness ratio and the resulting loading mode. The application of extra glass layers affects laminate thickness, but also the Young modulus mismatch, which are important factors for stiffness changes and final fatigue strength. The aspects of the thermal expansion coefficient of aluminium, carbon and extra glass layers could be an extra factor for different long-term thermal–mechanical behaviour. However, in the case of fibre metal laminates cured under high temperature (up to 180 °C) curing conditions the manufacturing stresses also can influence the initial stress-state of a laminate [45] despite the presence of protective glass layers. For this reason, the simple modification of an anti-corrosive barrier via thin glass fibres cannot be considered as critical for thermal shock resistance.

4 Summary

This paper presents an experimental analysis of the mixed mechanical–environmental long-term behaviour of carbon-based fibre metal laminates and their variations with glass

Fig. 7 The influence of thermal shocks on the fatigue life of SBS specimens

protective layers. The laminates were subjected to 1500 thermal cycles with a temperature range of 130 °C. The static and fatigue interlaminar shear strengths were tested before and after thermal conditioning. The fatigue life as well as laminate stiffness changes were analysed and compared in terms of the thermal conditioning effect. Based on the conducted research it was demonstrated that although there was a slight tendency to ILSS change after thermal shocks, statistical analysis did not show statistically significant differences between the ILSS values.

Based on results some conclusions were noted:

- the static interlaminar shear strength does not depend on thermal cycles or on the thin glass protective films applied between the metal and carbon layers.
- the fatigue response of carbon-based FMLs (and their variations with glass protective layers) is characterized by some visible thermal cycle dependence. The stable stiffness reduction in the tested laminates was observed with increasing fatigue cycles, due to the progressive fatigue damage accumulation. The thermally cycled laminates feature slightly smoother stiffness loss, while a more rapid decrease was observed in thermally untreated laminates. An additional factor of the laminate stiffness reduction after thermal cycling is the presence of additional glass fibres in both the 0° and 90° fibre orientations.
- an analysis of the fatigue life of the tested laminates subjected to thermal cycling revealed nine times fewer fatigue cycles of laminates with glass protectors after thermal cycles in comparison to the reference materials (laminates not subjected to thermal cycling).
- the mechanical long-term behaviour of carbon-based fibre metal laminates and their variants with glass protective layers is adversely affected by the earlier thermal-cyclic conditions. The main factor in that is the fact of Young modulus change and mismatch through laminate thickness with a simultaneous strength reduction of metal/composite interfaces due to thermal expansion effects.

Acknowledgements The project/research was financed within the framework of the project Lublin University of Technology-Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).

Funding Polish Ministry of Science and Higher Education (Contract no. 030/RID/2018/19).

Availability of data and material The raw/processed data required to reproduce these findings can be shared via request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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