FATIGUE BEHAVIOR OF DISSIMILAR WEATHERED RIVETED JOINTS OF HYBRID FIBER-METAL LAMINATE

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Abstract. Dissimilar riveted fiber-metal laminate joints were weathered and subsequently subjected to tension fatigue loading. It is concluded that joint configuration strongly determines fatigue behavior, especially at lower peak loads. Hygrothermal aging is shown to be a more hostile form of conditioning than repeated thermal shock.

Introduction

Hybrid fiber-metal laminates (FML) comprise alternating layers of polymer resin composite reinforced with continuous fibers and metallic alloys, exhibiting high resistance to crack growth combined with other attractive properties for the aviation industry [1]. Aircraft materials are subject to various types of mechanical loads, especially fatigue, and to different environmental factors that negatively affect their integrity throughout their service life [2]. Thus, it is important to evaluate the effects of repeated thermal shocks and hygrothermal aging on the fatigue-life of dissimilar joints of FML. In this work, dissimilar riveted joints of Glare®-FML and 2024-T3 aluminum alloy sheets were subjected to repeated thermal shock and hygrothermal aging, followed by fatigue testing to assess their effects on the fracture mechanisms and fatigue-life of the mechanical joints.

Materials and Test Specimens

Dissimilar joints were prepared using the following materials:

a. 1.6 mm thick 2024-T3 Al-alloy sheet;

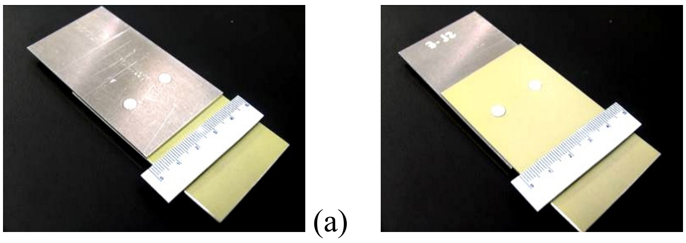
b. 1.6 mm thick Glare-5 FML sheet composed of two 0.5 mm thick layers of Al 2024-T3 alloy sandwiching four layers of S2 glass fiber-reinforced epoxy resin in a 0°/90°/90°/0° configuration.

Plaques were joined by two rivets aligned perpendicularly to the fatigue loading direction (0°).

Two classes of joints were manufactured:

a. Al-Gl (Fig. 1a), in which countersunk holes were machined in the Al-alloy sheet;

b. Gl-Al (Fig. 1b), in which countersunk holes were drilled in the Glare sheet.



(a) (b)

Fig. 1: Dissimilar riveted joints: (a) Al-Gl; (b) Gl-Al.

Procedures

Thermal cycling. Two Al-Gl and two Gl-Al joints were subjected to repeated thermal shock in an Envirotronics® model TSV.5-2-2-2-AC system. Two thousand complete cycles (-50°C→+80°C→ -50°C) were applied sequentially, with a dwell time of 15 minutes at each temperature. Extreme temperatures were chosen based on commercial aircraft flight envelope [3]. After thermal cycling, the specimens were wrapped in aluminum foil and conditioned in an environment with 100% relative humidity until fatigue tests were performed.

Hygrothermal aging. Two Al-Gl and two Gl-Al joints were oven-dried at 60°C for 24 hours, weighed on an analytical balance and kept for 140 days at 90% humidity and 80°C in a Marconi® MA 835/UR hygrothermal chamber. Upon their removal from the chamber, the specimens were weighed to determine their absorbed moisture content, after which they were stored in a moist environment until fatigue tests were carried out.

Fatigue tests. A MTS® Landmark mechanical testing system with a capacity of 100 kN was used. Constant amplitude loading tests were conducted at room temperature, using a loading ratio of +0.1 applied at a frequency of 10 Hz in sinusoidal waveform. Two peak fatigue stress levels were used, respectively 49 MPa and 56 MPa, which were selected based on Ref. 4 in which the fatigue behavior of non-conditioned Al-Gl and Gl-Al joints was studied.

Failure analysis. The main macro-mechanisms of fatigue failure were identified, and the sequence of events was proposed taking as baseline the results reported by [4].

Results and Discussion

Moisture up-take. The Al-Gl joints absorbed 0.45% in weight of moisture compared to 0.87% for Gl-Al joints. This is credited to the fact that in Gl-Al joints, the Glare sheet contains countersunk holes to fit angled rivet heads, which increases the area available in the FML for moisture ingress. Because Glare is the joint element that effectively absorbs moisture, this tendency is highly favored in Gl-Al configuration. In Al-Gl disposition, rivet tails seal the flat bottom holes in Glare against moisture entry and the aluminum alloy sheet shields the other side of the FML, thus minimizing water absorption.

Fatigue tests. S-N curves obtained by Ref. 4 for pristine Al-Gl and Gl-Al joints are shown in Fig. 2 and data points collected in this study are plotted concomitantly. Hereinafter, tested specimens are identified by letters from A to H.

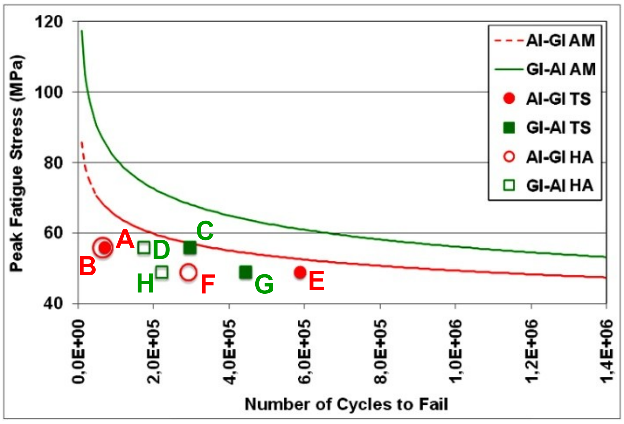


Fig. 2: S-N curves derived from as-manufactured (AM) Al-Gl and Gl-Al joints [4], and S-N data points obtained from testpieces subjected to repeated thermal shock (TS) and hygrothermal aging (AH), respectively.

The following conclusions can be drawn from Fig. 2:

- Fatigue-life of fastened joints was more deteriorated by hygrothermal aging than by repeated thermal shock.
- Gl-Al joint configuration was more sensitive to both environmental conditioning.
- These tendencies were more evident under the peak stress of 49 MPa.
- Both the joint geometries exhibited lower-bound results after environmental conditioning, with Gl-Al joint showing the poorest performance under lower stress (49 MPa) and Al-Gl joint exhibiting the worse performance under higher stress (56 MPa).

The higher sensitivity of Gl-Al joint to environmental factors corroborates the moisture absorption results reported in the moisture up-take item above. E vs. G results in Fig. 2 indicate that moisture up-take probably occurred in Gl-Al joint configuration in response to repeated thermal shock, thus enabling freeze-thaw cycle damage to develop [5]. Deleterious effects of both types of conditioning on Gl-Al joint fatigue-tested under lower peak stress was more evident due to the longer time this dissimilar joint was subjected to cyclic mechanical loading, which allowed the failure mechanisms resulting from subtle environmental conditioning damage introduced previously to become fully operative.

Failure analysis of joints

Maximum stress of 56 MPa

Non-conditioned Al-Gl joint (Al-Gl AM curve in Fig. 2). Fig. 3 depicts the Al-Gl joint fractured at 302,027 fatigue cycles by [4]. Fretting in maximum pressure points at the hole borders is promptly noticed, with cracking and complete fracture of the countersunk Al-alloy sheet. A visual inspection of the inner metal layer of Glare sheet did not allow for the detection of possible damage on it. Fragmentation and loss of 30-50% of conical rivet heads are clearly observed.


(a) (b)

Fig. 3: (a) Fatigue fracture of Al-Gl joint without previous conditioning [4]; (b) Magnified view.

Thermally cycled Al-Gl joint (data point A in Fig. 2). Fig. 4 shows the Al-Gl joint fractured after 69,326 fatigue cycles, which is a much shorter life than as-manufactured specimen (Fig. 3). Failure mode includes pull-out of rivet shanks from matching heads and extensive cracking of inner metal layer of the flat-bottom hole Glare sheet, with cracks initiating at straight hole edges. This lengthy cracking rendered the joint increasingly compliant during fatigue testing, thus favoring rivet fracture mechanisms which in turn determined specimen's fatigue-life. Repeated thermal shock damaged hole border regions of Glare plaque, expediting the onset of fatigue crack growth at the inner metal layer and reducing testpiece´s fatigue-life. Freeze-thaw effects caused interfacial damage, thus undermining adhesion between layers of Al-alloy and glass fiber/epoxy composite within Glare-FML as well as impairing mechanical strength and stiffness of its composite core. As a result, overloaded metallic outer layers speed up both crack initiation and propagation stages in Glare, further contributing to reduce the specimen's life under cyclic loading.

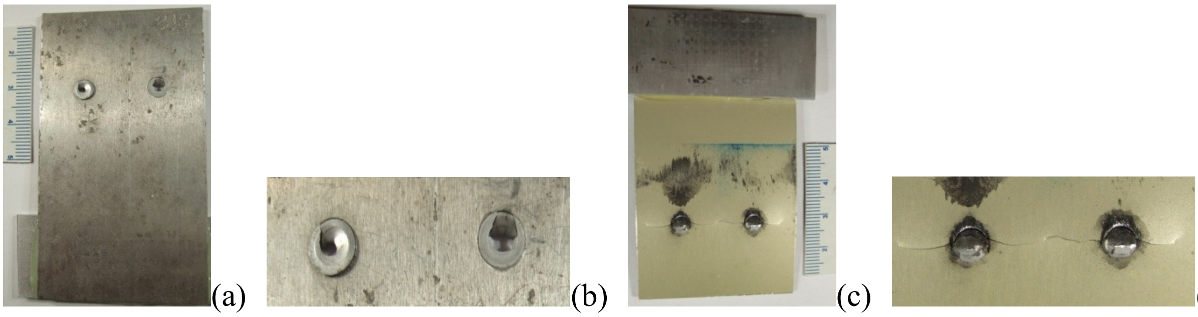

(a) (b) (c) (d)

Fig. 4: (a) Outer face of countersunk Al-alloy sheet of the Al-Gl joint (A); (b) Detailed view; (c) Inner face of straight-bottom hole FML sheet; (d) Detailed view.

Hygrothermally aged Al-Gl joint (data point B in Fig. 2). Fig. 5 presents the Al-Gl specimen which endured 66,406 fatigue cycles, which is very close to the fatigue-life displayed by the previously thermally cycled joint shown in Fig. 4. The observed failure mechanisms and their chronological sequence seem to be quite similar to those established for Fig. 4, so that consistency and robustness of obtained results is ascertained. Due to this observed similarity, fretting is probably not the controlling mechanism of failure process, since hygrothermal aging would favor this effect on the subsequent fatigue loading more effectively than repeated thermal shock. It can be concluded that applied stress must have been sufficiently high to preclude the complete development of fretting mechanism.

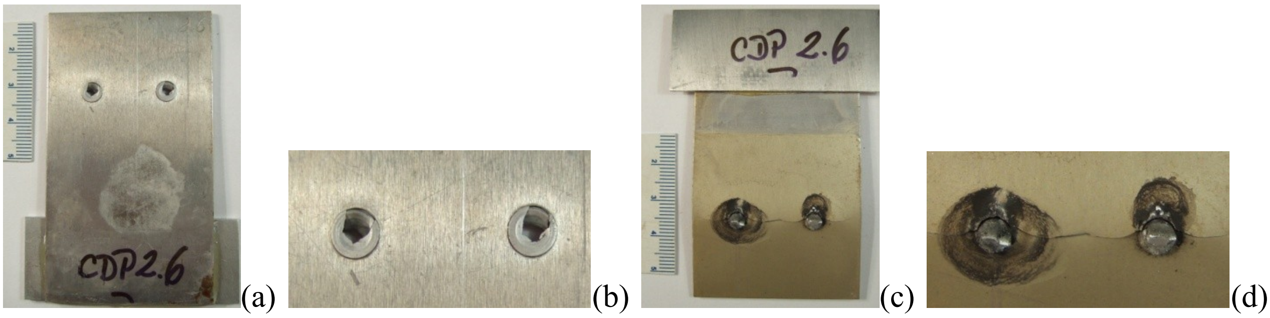


Fig. 5: (a) Outer face of countersunk Al-alloy sheet of the Al-Gl joint (B); (b) Magnified view; (c) Inner face of flat-bottom hole Glare sheet; (d) Magnified view.

Non-conditioned Gl-Al joint (Gl-Al AM curve in Fig. 2). Fig. 6 depicts the Gl-Al joint fractured under fatigue at 667,708 loading cycles by [4]. Fretting at rivet hole boundaries, as well as complete cracking of inner metal layer of the countersunk Glare sheet, alongside extensive fragmentation of both rivet heads are clearly noticed. In addition, almost complete through-the-thickness fracture of the straight-bottom hole Al-alloy sheet, with crack starting on its inner face, was unveiled. Fretting-induced cracking at the inner layer of Glare occurred in positions away from hole edges, thus preventing rivet heads from passing through the holes in the inner metal layer of countersunk FML sheet, leading to its extensive delamination.

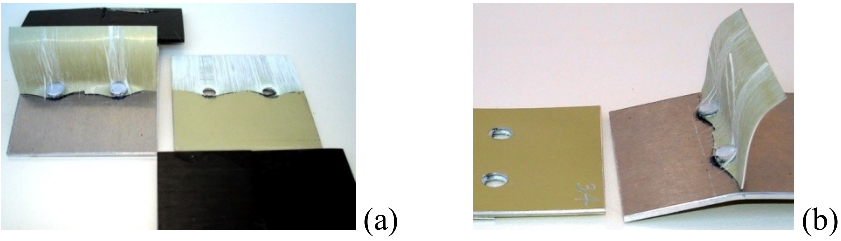


Fig. 6: Gl-Al joint fatigue-tested by [4]. (a) Frontal view; (b) Lateral view.

Thermally cycled Gl-Al joint (data point C in Fig. 2). Fig. 7 shows the Gl-Al joint fractured after 297,772 applied fatigue cycles, half the lifespan of non-conditioned specimen shown in Fig. 6. Specimen failure was due to extensive cracking of inner metal layer of Glare sheet and partial fragmentation of one fastener head. This process was accelerated by increasing specimen compliance due to the aforementioned cracking. Upon reaching a critical combination between damage extension of conical rivet heads and cracking degree at the inner metal layer of Glare-FML sheet, the undermined rivet came out through the Glare plaque thus overloading the twin fastener, which ruptured due to pure shear resembling a guillotine effect.

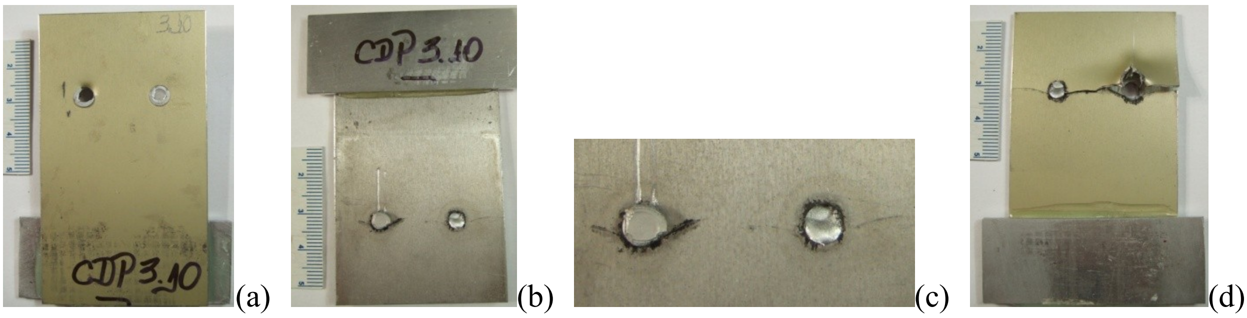


Fig. 7: (a) Outer face of countersunk Glare sheet of the Gl-Al joint (C); (b) Inner face of flat-bottom hole monolithic Al-alloy sheet; (c) Detailed view; (d) Inner face of Glare sheet.

Hygrothermally aged Gl-Al joint (data point D in Fig. 2). Fig. 8 outlines the Gl-Al joint that failed catastrophically at 174,851 fatigue cycles, half the lifespan of the preceding joint (Fig. 7). This failure was basically due to transverse cracking of inner metal layer of the countersunk Glare sheet, boosted by accelerated fretting due to corrosion that took place during previous environmental conditioning. In the final stages of failure process, partially pierced rivet heads were pulled out through the Glare sheet. However, conjoined action of moisture and temperature during previous hygrothermal conditioning degraded and swelled the glass-epoxy core of Glare, thus reducing its mechanical properties [6-10]. This finding is corroborated by Figs 8c,d, which show entrapment and tearing of the expanded composite core layer under one completely fragmented fastener head.

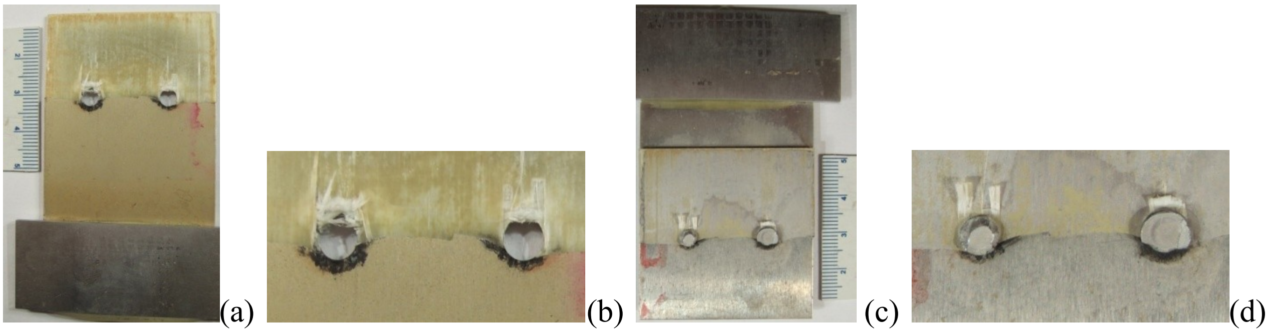


Fig. 8: (a) Inner face of countersunk Glare sheet of the Gl-Al joint (D); (b) Detailed view; (c) Inner face of straight-bottom hole Al-alloy sheet; (d) Detailed view.

Maximum stress of 49 MPa

Non-conditioned Al-Gl joint (Al-Gl AM curve in Fig. 2). Fig. 9 shows the non-conditioned Al-Gl joint fatigue fractured at 679,247 cycles by [4]. This joint is remarkably similar to that depicted in Fig. 3, which was also fatigue-tested without previous conditioning, but at a higher stress (56 MPa). Fretting is quite visible at maximum pressure contact regions between matching plaques, so are full cracking of countersunk Al-alloy sheet, permanent deformation of part of one rivet head as well as fractional splitting of the second fastener head.

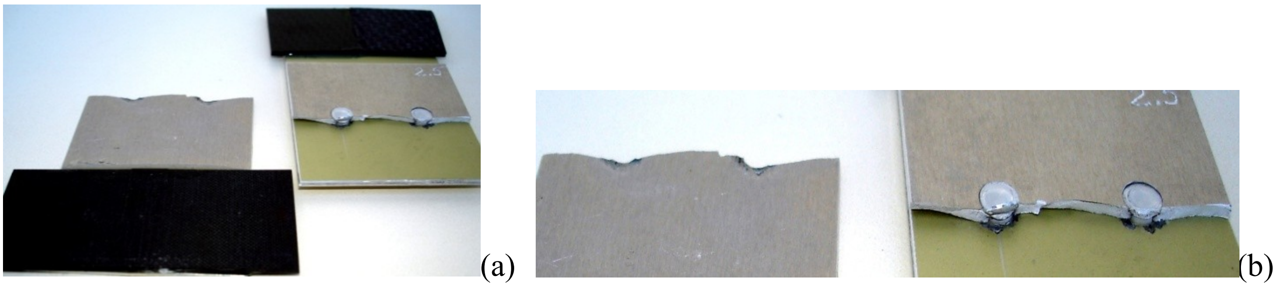
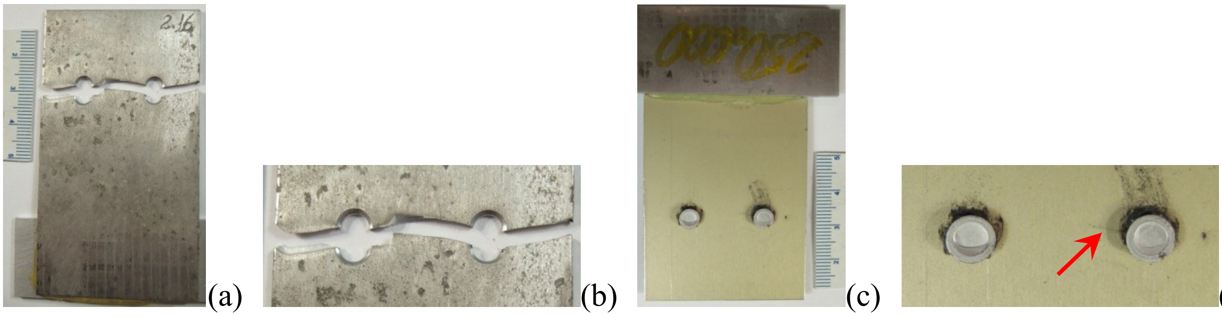


Fig. 9: (a) Al-Gl joint without previous conditioning fatigued tested by [4]; (b) Magnified view.

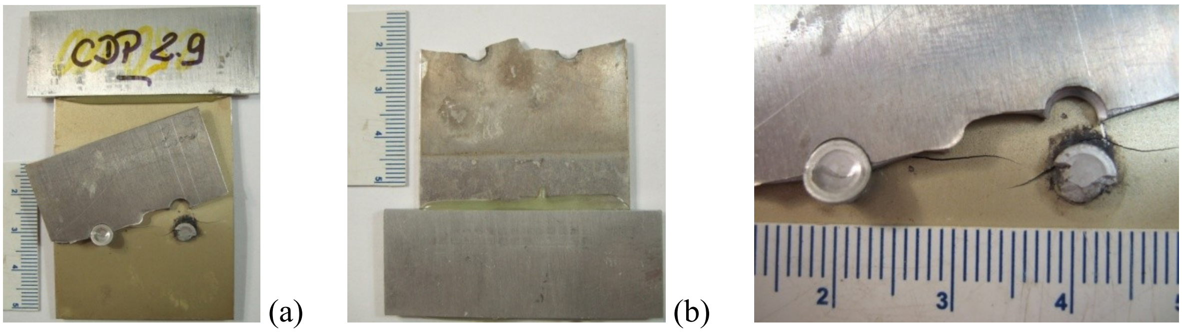
Thermally cycled Al-Gl joint (data point E in Fig. 2). Fig. 10 shows the Al-Gl joint subjected to repeated thermal shock and then fatigue-tested up to failure at 587,443 cycles, where the predominant mechanism is complete fracture of countersunk Al-alloy sheet. Failure mode of Al-Gl joints in Figs 9 and 10 is visually very similar, except for entrapment of part of the Al-alloy sheet in the first case due to slight displacement of crack nucleation sites from the hole corners. Crack nucleation locus are polar in non-conditioned joint (Fig. 9) but lateral in thermally cycled joint (Fig. 10), leading to somewhat different crack paths between these specimens. Fatigue-life difference between these specimens is not statistically significant (~10%), indicating that the effect of previous environmental conditioning was negligible. This deduction has to be confirmed by checking for the presence of cracking at the inner metal layer of Glare in non-conditioned joint (Fig. 9), as indicated by an arrow in Fig 10d.



(a) (b) (c) (d)

Fig. 10: (a) Outer face of countersunk monolithic Al-alloy of the Al-Gl joint (E); (b) Detailed view; (c) Inner face of flat-bottom hole Glare sheet; (d) Detailed view.

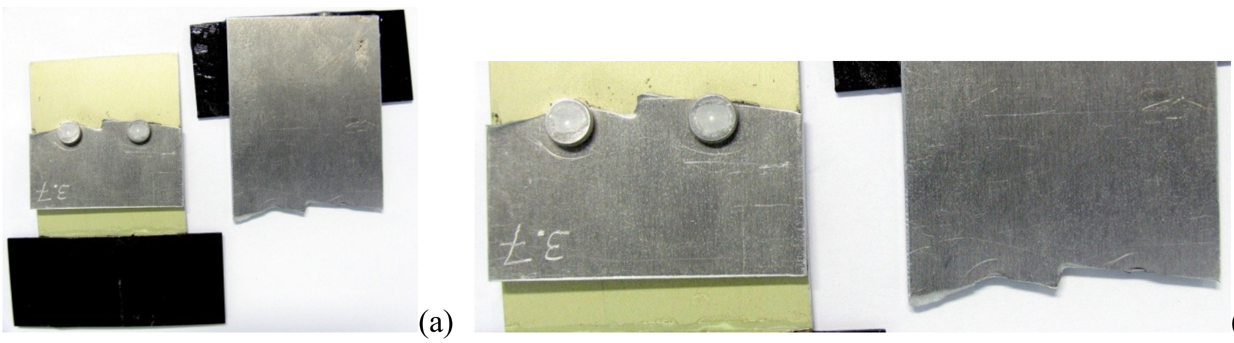
Hygrothermally aged Al-Gl joint (data point F in Fig. 2). Fig. 11 images the hygrothermally aged Al-Gl joint fractured after 292,529 fatigue cycles, half the lifetime of the specimen presented in Fig. 10. Although the predominant failure mechanism was rupture of monolithic Al-alloy sheet (see Fig. 10), previous environmental conditioning also favored cracking of inner metal layer of Glare-FML, albeit not sufficiently to cause it to collapse before the matching monolithic Al-alloy sheet. Simultaneous heat and moisture action created favorable conditions for fretting development, thus facilitating crack nucleation on both metallic surfaces of contacting sheets and advanced rupture of the specimen. Both rivet heads were markedly damaged, with 50% of one fastener head being fragmented and the other one undergoing extensive plastic deformation at the very final detachment between sheets.



(a) (b) (c)

Fig. 11: (a) Overall view of Al-Gl riveted joint (F); (b) Inner face of countersunk Al-alloy sheet; (c) Detailed view of rivet heads, fracture of Al-sheet, and Glare sheet cracking.

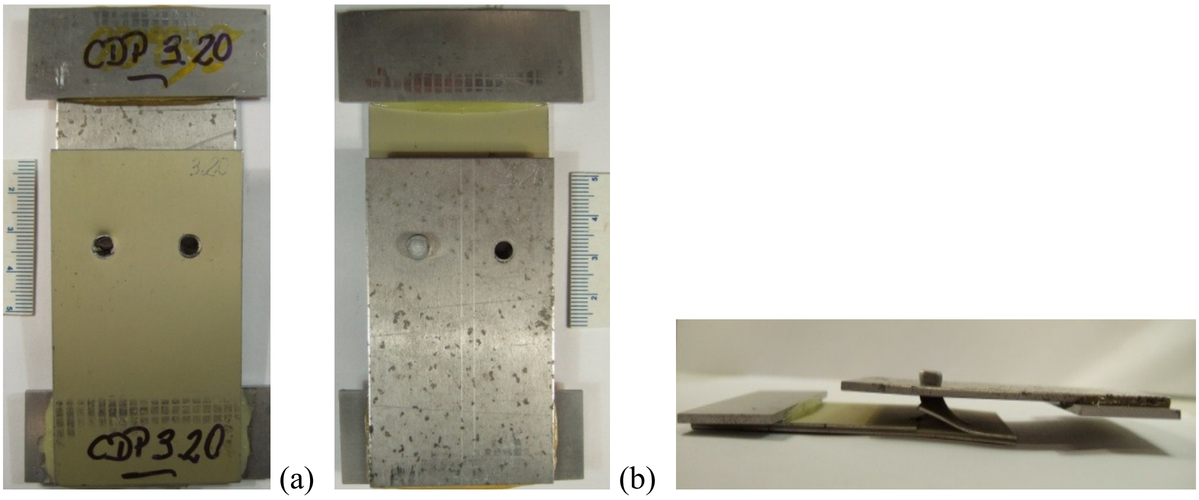
Non-conditioned Gl-Al joint (Gl-Al AM curve in Fig. 2). Fig. 12 depicts the Gl-Al joint fractured by fatigue at 1,309,892 cycles [4], showing complete rupture of flat-bottom hole Al-alloy sheet. Cracks nucleated close to poles of drilled rivet holes, at some distance from their borders, so that subsequent cracking caused entrapment of the fractured portion of Al-alloy sheet. The same macro-mechanism had already been observed in non-conditioned Gl-Al joint that was fatigue-tested under a peak stress of 56 MPa (Fig. 6), when fretting-generated cracks also developed in the bulk material instead of at drilled hole corners. However, in that case, fractured sheet was the countersunk Glare one, and not the monolithic straight-bottom hole Al-alloy plaque.



(a) (b)

Fig. 12: (a) Non-conditioned Al-Gl joint tested under fatigue by [4]; (b) Magnified view.

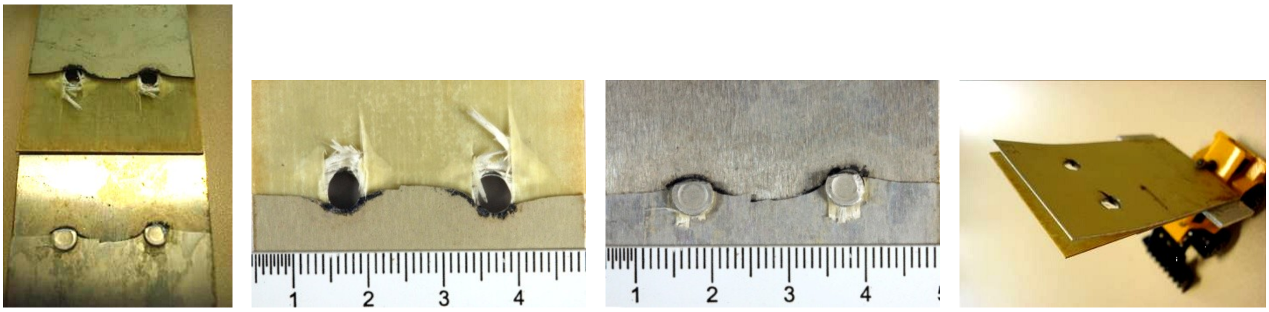
Thermally cycled Gl-Al joint (data point G in Fig. 2). Fig. 13 illustrates the Gl-Al joint fractured after 444,472 fatigue cycles, where failure comprised partial or total fragmentation of rivet heads, and corresponding partial or total cracking of inner metal layer of countersunk Glare sheet. Whereas the rivet whose head was totally fragmented during fatigue loading was pulled out at the end of the failure process, partially broken off rivet head caused delamination between inner metal and matching glass-epoxy core layers, aided by fatigue pre-cracking of the former layer. Therefore, the root cause of joint failure was synergy between the interdependent fracture mechanism of rivet heads and fatigue cracking of inner metal layer of Glare. Fatigue-life of this joint was three-fold shorter than that of corresponding non-conditioned joint (Fig. 12), signalizing how deleterious repeated thermal shock can be for its subsequent fatigue performance under a peak stress of 49 MPa.



(a) (b) (c)

Fig. 13: (a) Outer face of countersunk Glare sheet of the Gl-Al joint (G); (b) Outer face of straight-bottom hole monolithic Al-alloy sheet; (c) Lateral view of fatigue-fractured joint.

Hygrothermally aged Gl-Al joint (data point H in Fig. 2). Fig. 14 shows the Gl-Al joint fractured after 223,000 fatigue cycles, whose fracture aspects appear to be very similar to that of joint presented in Fig. 8, which was also subjected to hygrothermal aging but fatigue-tested to a peak stress of 56 MPa. This specimen presented complete cracking of inner metal layer of Glare, with cracked portion of this layer remaining attached by the rivet heads to the flat-bottom hole Al-alloy plaque. Intensive and extensive fretting was developed at hole boundaries, besides massive deterioration of rivet heads, notwithstanding to a lesser extent than that observed under higher peak stress (Fig. 8). The same reasoning exerted in the analysis of Fig. 8 with regard to hygrothermal aging effect on swelling and degradation of glass-epoxy composite core of Glare holds for Fig. 14, since entrapment of inner metal layer of Glare and presence of composite fragments under rivet heads occurred as well in the latter case. The unfeasibility of detecting eventual internal cracking in non-countersunk Al-alloy sheet in Fig. 14 is equivalent to Fig. 8. However, two facts clearly distinguish Fig. 14 from Fig. 8, namely, cracking of outer metallic layer of Glare and extensive delamination between this and the glass-epoxy composite core layers of the FML, as seen in Fig. 14. The latter impairing mechanism, which was caused by previous hygrothermal conditioning, weakened bonding between metal and composite layers, and became evident during fatigue load at the peak stress of 49 MPa owing to the longer timespan in which Gl-Al joint was cyclically loaded as compared to the time spent under the peak stress of 56 MPa. This interfacial failure unbalanced the mechanisms of support and distribution of mechanically applied load, thus inducing and accelerating cracking in the outer metal layer of Glare, although the exact chronological rank of these events cannot be precisely confirmed. Lastly, fretting favored and speeds up by previous environmental conditioning shortened fatigue-life of joint by reducing the time for crack nucleation in inner metal layer of Glare.



(a) (b) (c) (d)

Fig. 14: (a) Inner faces of Glare (top) and monolithic Al-alloy sheets (bottom) of the Gl-Al joint (H); (b,c) Detailed views of previous image; (d) Extended delamination of Glare sheet.

Conclusions

- Hygrothermal aging was more aggressive than repeated thermal shock in reducing fatigue-life of dissimilar Glare FML joints.
- The joint configuration most sensitive to environmental conditioning was Gl-Al.
- These models were more perceptible at lower peak stress.
- Both the Gl-Al and Al-Gl joints exhibited lower-bound results after previous conditioning, the former joint under lower and the latter one under higher peak fatigue stresses.
- A full failure analysis of tested joints corroborated S-N curve results and provided useful information about fracture mechanisms and their chronological sequence.

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