Assessment of the effects of thermal shock cycles on the fatigue behavior of damaged Glare-to-aluminum joints

T. A. Barreto[1], J. R. Tarpani[1]

[1]*Universidade de São Paulo, Escola de Engenharia de São Carlos, SP, Brazil*
e-mail: thays.barreto@usp.br

Abstract

Before selecting a material for a specific application, it is very important to know its fatigue behavior in the structure over operational conditions. Glare-5 is a strategic material for space applications due to its improved impact performance, and could be employed in regions where there's high risk of impact on in-orbit structures. However, yet is to be defined about its behavior over similar-to-space conditions, especially when it comes to its application on fatigue critical, but inevitable, structures such as riveted joints. This study aim at defining the effects of thermal shocks, like the ones that occur on in-orbit structures, over already damaged Glare-to-aluminum riveted joints.

Keywords: fiber-metal laminate; fatigue behavior; riveted joints; Glare; space application.

Introduction

Major advances in the search for light-weighted high-strength materials for the aerospace industry led to the development of Glare™, a fiber-metal laminate (FML) composed of alternatively stacked aluminum alloy layers and glass-fiber/epoxy composite layers. The high design flexibility of the composite layers in FMLs led to the development of several Glare variants by changing the position of the fibers of the prepreg plies in the composite layers and improving the materials performance over specific loadings [1].

The improved impact properties of the variant Glare-5, which is characterized by a 0°/90°/90°/0° stacking sequence in the composite layers [1], make it ideal for in-orbit applications, such as high impact risk areas of satellites or space stations. However, materials used on exterior spacecraft surfaces are subjected to many environmental threats that can cause degradation, like great temperature variations over small periods of time, thermal shocks, which might impair the material's performance [2].

Considering the need for more information upon de behavior of a component prior to its employment in aerospace structures and since fatigue damage is prone to occur in structural joints [1], major attention has been dedicated to the assessment of the failure mechanisms developed in such structures [3–6]. The Group of Engineered Composite Materials (GECoM – EESC USP) has developed work on identifying the fatigue behavior of single lap riveted joints of Glare-5 and aluminum alloy over several conditions[5–6]. The present study aims at assessing the failure mechanisms of damaged joints submitted cycles of thermal shocks in order to assess if the effects of thermal shocks over damaged joints' performance.

Experimental Procedure

The specimens employed in this study were single lap riveted joints composed 1.7 mm-thick panels of FML Glare-5 and monolithic 2024-T3 aluminum alloy. This Glare-5 material is composed of two 0.5 mm-thick layers of 2024-T3 aluminum alloy and unidirectional high-strength S2-grade glass fibers/epoxy matrix composite, a 2/1 architecture, provided by Comtek Advanced Structures™ (Canada).

Two rivets, positioned symmetrically and orthogonally to the loading direction, joined the panels. The Riveting process followed stringent Brazilian aeronautic standards. The rivets were countersunk type MS20426 AD 4-7 rivets, made of 2117-T4 alloy. Figure 1 presents the specimens dimensions and rivet positioning.

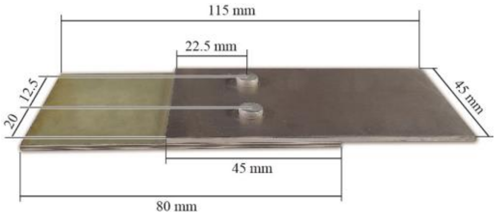
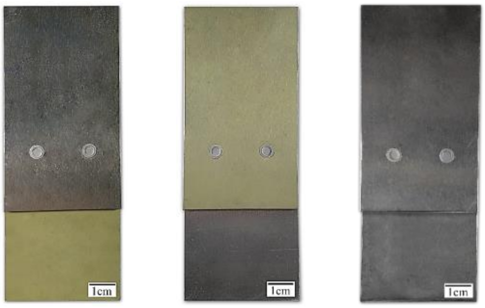


Figure 1 – Specimens dimensions, ± 0.1 mm.

The test program comprised three specimen configurations, namely Al-Gl, Gl-Al and Al-Al, presented in Figure 2. Where the first and second ones are hybrid joints with either the aluminum or the Glare panel as the countersunk one, respectively. The last joint is a traditional one taken as reference.



Al-Gl Gl-Al Al-Al

Figure 2 – Specimen configurations.

In order to evaluate the effect of thermal shocks over damaged joints, the specimens were damaged through loading cycles. This damage induction was conducted in a MTS®-810 (250 kN maximum load) with 60 MPa peak stress, at room temperature, with load control, slight positive load ration (R=+0.1), to prevent specimen buckling, and 10 Hz frequency, to avoid heating.

The damaged specimens were then exposed to 500 thermal shock cycles in boiling water (+100 °C) and liquid nitrogen (-194 °C). They were immersed for 10 min. in each fluid to ensure thermal equilibrium.

Fatigue behavior of the specimens was assessed by subjecting them to up-to-failure fatigue cycles with 49 MPa peak stress in the same conditions as during damage induction. The development of the failure mechanisms observed by performing the fatigue tests in rounds, with specimens being periodically removed from the testing machine for visual, microscopic, ultrasonic and eddy current non-destructive inspections (NDIs).

Results and Discussion

Generally, Al-Al and Gl-Al specimens showed no detectable damage after the induced damage cycles. The exceptions are the specimens Al-Al 1.14 and Gl-Al 3.24. The first one developed a crack in the left rivet’s head and bottle opener effect signs (damage around rivet heads and rivet holes [4]). The other developed light bottle opener effect signs.

The Al-Gl specimens presented visible damages, such as bottle opener effect signs and cracks on the rivet heads, except the 2.15 specimen. The specimen 2.24 showed extensive damage to the rivet heads and cracks nucleating from rivet holes in the countersunk panel, a Multiple Site Damage (MSD) condition [3],.

NDIs performed before and after the thermal shocks indicated no detectable aggravation of damage after the conditioning.

After the first round of fatigue cycles, 40,000 cycles, Al-Al specimens developed bottle opener effect signs and cracks in the rivets’ heads. Specimens 1.14, 1.18 and 1.21 also resented slight bending of the non-countersunk panel.

After 80,000 fatigue cycles all Gl-Al specimens also developed slight signs of bottle opener effect around rivets' heads combined to a slight bending of the Al counterpart. Ultrasonic inspection indicated small delamination around rivets.

The Al-Gl specimens presented the greatest aggravation of damage. After 120,000 fatigue cycles, they developed cracks in the rivet heads and significant signs of bottle opener effect. In addition, after 27,500 fatigue cycles, the 2.24 specimen fractured.

For this specimen, thermal shock conditioning haven't changed the main failure mechanism from as-manufactured specimens (i.e. non-conditioned specimens) [5], it remained countersunk panel failure. However, the failure of the Al-Gl 2.24 specimen was accompanied by other failure mechanisms in advanced development stages, such as great damage to the rivet heads, fretting corrosion marks on the mating surfaces and MSD cracks on the mating surface of Glare with extensive delamination in the region. Figure 3 highlight the damages on the fractured specimen.

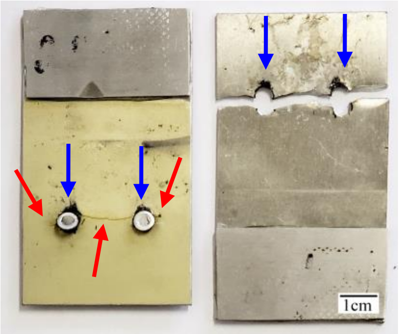


Figure 3 – 2.24 specimen. Cracks pointed by green arrows and fretting by red ones.

Although more data is mandatory to make assumptions, we can observe that the Al-Gl specimens were most impaired by the thermal shocks compared to as-manufactured specimens [5]. Thermal shocks even seem to be more detrimental to this configuration than great amplitude thermal cycling [6].

Conclusions

Single lap riveted joints were damaged and submitted to thermal shocks. Although tests are still in progress, we can conclude that thermal shocks are more harmful to Al-Gl specimens than to Gl-Al and Al-Al ones. The testing program will continue up to the fracture of all specimens and the assessment of the failure mechanisms developed.

This work will result in a detailed report on the development of the failure mechanisms and an analysis of the effects of thermal shocks relative to as-manufactured specimens.

Acknowledgments

This study was financed in part by Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

References

[1] J. W. Gunnink, A. Vlot, T. J. De Vries, and W. Van Der Hoeven, “Glare Technology Development 1997-2000,” *Appl. Compos. Mater.*, vol. 9, pp. 201–219, 2002.

[2] NASA, “Space Environmental Effects,” in *A Researchers Guide to International Space Station*, 2009.

[3] B. R. Mosinyi, “Fatigue damage assessment of high-usage in-service aircraft fuselage structure,” 2007.

[4] A. C. S. P. Tarpani, T. A. Barreto, and J. R. Tarpani, “Fatigue failure analysis of riveted fiber-metal laminate lap joints,” *Eng. Fract. Mech.*, vol. 239, no. August, p. 107275, 2020.

[5] C. E. B. Martinez and J. R. Tarpani, “Aplicação de Técnicas de Raios-X na Monitoração de Trincas de Fadiga em Juntas Rebitadas de Glare,” São Carlos, 2006.

[6] R. A. Oliveira and J. R. Tarpani, “Inspeção Não-Destrutiva e Análise de Falha de Juntas Mecânicas de Glare Fadigadas após Ciclagem Térmica de Grande Amplitude,” São Carlos, 2010.