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Thermally Induced Failure of Bonded Composite-Metal Joints

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ABSTRACT

Integration of composite materials into larger structures may require secondary bonding to form durable joints with metal components. However, due to differences in thermal expansion, significant thermally induced stresses can form within the bond line that can lead to the initiation of cracks. Such cracks were observed in a secondarily bonded joint where an infusion resin was used to bond a glass fiber reinforced polymer (GFRP) cylinder to an aluminum cylinder at sub-ambient temperatures. In this study, a combination of experiments and computational simulations were used to replicate the failure and provided a path forward for development of a more resilient epoxy infusion resin. For large structural parts, the choices for a replacement epoxy are virtually limitless and fabrication of these parts can be both costly and time consuming. In situations like these, basic tensile characterization techniques at sub-ambient temperatures can serve as a screening mechanism for potential replacement epoxy candidates and a scaled down structural design can validate the effectiveness of the selection at a much lower cost. The focus of this study will be on determining the relevant material and geometric parameters necessary to develop and perform a representative validation experiment for a complex problem.

Keywords: Residual Stress, Composites, Failure, Polymer, Bonding

INTRODUCTION

Hybrid joints between composite and metal adherends are frequently produced with a secondary adhesive. In many aerospace and energy applications, these joints are subjected to extreme service temperature ranges greater than 100°C and with it, high levels of thermal stress. Due to the coefficient of thermal expansion (CTE) mismatch between not only the adhered materials, but also the adhesive itself, significant residual stresses can be generated that may lead to bond line failure. In one such application an infusion resin, INF114/251HT, is used to form a cylindrical lap joint between an outer aluminum tube and an inner GFRP tube. In such a configuration, the GFRP (~15ppm/°C) and 6061-T6 aluminum (~25ppm/°C) have much lower CTEs than the infusion resin (~75ppm/°C). Exacerbating the issue is that many high strength epoxies require an elevated cure which adds to the change in temperature from the stress-free temperature to the service temperature (ΔT). With the cylinder-in-cylinder configuration of the adhesive joint, this leads to a significant tensile stress within the epoxy bond line at temperatures below the stress-free temperature (Fig. 1).

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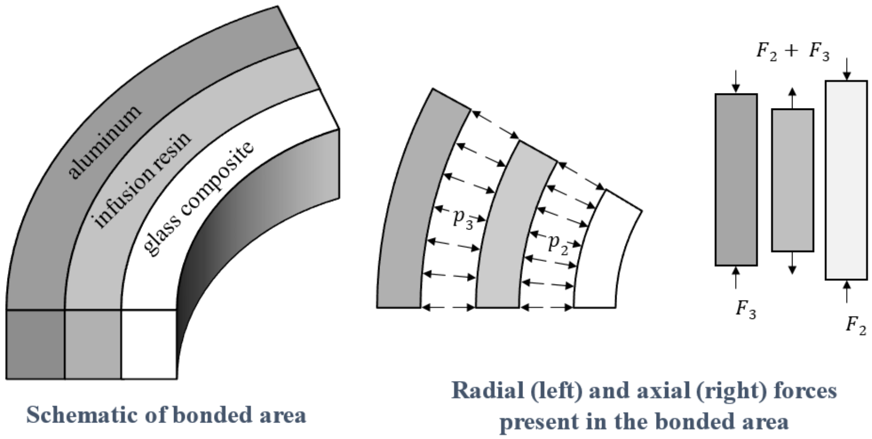

Fig. 1: Forces acting on cylindrical joint due to CTE mismatch

During testing of this joint at sub-ambient temperatures, audible cracking was observed and subsequent X-ray Computed Tomography (XCT) of the joint confirmed tensile failure within the epoxy bond line (Fig. 2).

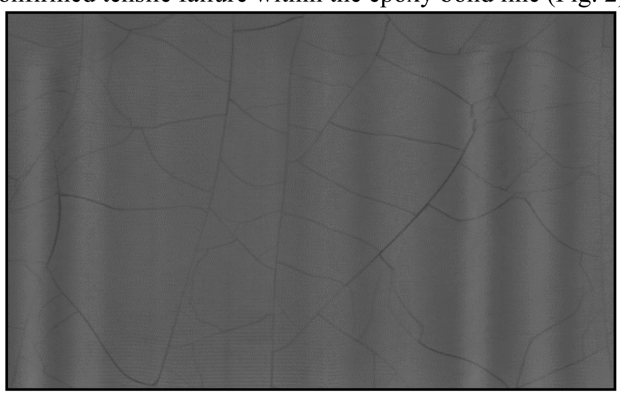

Fig. 2: XCT image of failed bond line

While these cracks remain within the bond line and the inner cylinder is still bonded to the outer cylinder, they serve as interfacial crack initiation sites that may lead to adhesive failure over the service life of the part. As the cracks appear to be due to tensile failure, a replacement epoxy with sufficient ductility at the low end of the service temperature range, due to the greatest tensile thermal stress at that temperature, must be found.

APPROACH

Due to the nearly limitless number of epoxy/hardener combinations that exist, it is important to narrow the search by focusing on the relevant material properties for the application. Since the aluminum and GFRP are so much stiffer than any epoxy, a change in elastic modulus would have minimal impact. Also, because the failure is driven by thermal strain, variations to the bond line thickness would also not have a large impact. This was backed up by an elastic analysis that varied the bond line thickness and reported a small effect on the axial, radial, and circumferential strains (Fig. 3).

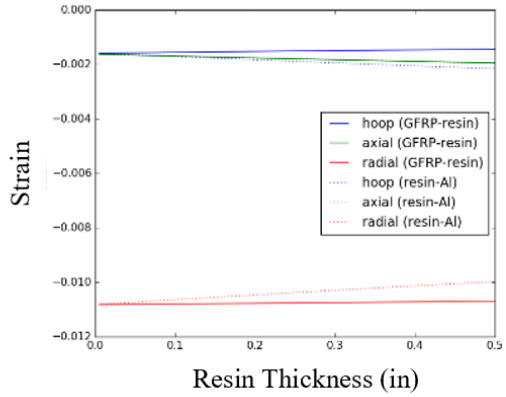

Fig. 3: Effect of bond line thickness on infusion resin strain components

The key properties that were considered included: tensile strain at sub-ambient temperatures, low viscosity for ease of manufacture, and a glass transition temperature greater than the high end of the service temperature. While factors such as low CTE and low cure shrinkage would have a strong effect on the results, these material properties do not vary widely within the class of epoxy resins.

Tensile testing was performed on 23 different combinations of epoxy, hardener, hardener blends as well as cure temperatures and post-cure temperatures. The solution was found using a proprietary formula developed by Adriana Pavia-Sanders, Nalini Menon, and April Nissen named ANA using their first initials from the Materials Chemistry Department at Sandia National Laboratories in California. The original infusion resin only showed a failure strain at -54°C of approximately 1.2%, while ANA showed ductility into the 6% range (Fig. 4).

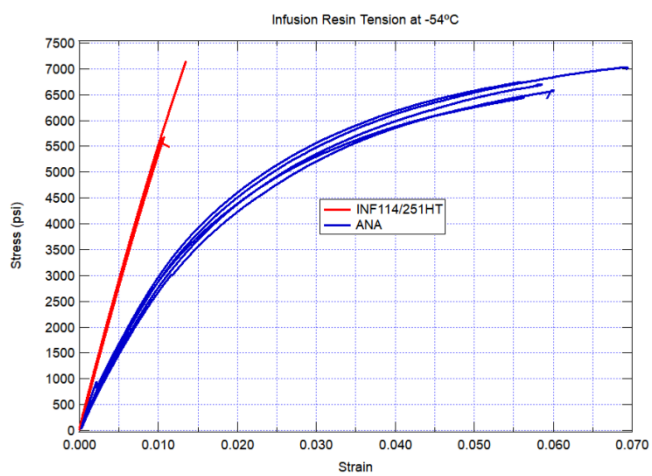

Fig. 4: Tensile stress-strain curves of original infusion resin and replacement ANA resin

VALIDATION

The tensile test results appear promising, but they are being tested under uniaxial stress. The stress state in the actual joint is triaxial due to the change in boundary conditions. In situations such as this, a validation experiment is necessary to prove that the material change will improve the design. However, the actual component is expensive to produce and uses materials with a long lead time so an intermediate test step is necessary that increases the complexity of the test but is simple enough that multiple test units can be produced quickly and economically while maintaining the proper stress state. Elastic stress analysis of the component's joint was compared to a scaled down, ring-in-ring configuration. Prior analysis showed that the part diameter, bond line thickness, and outer and inner ring thicknesses had little impact on the stress state in the adhesive bond line (Table 1).

Table 1: Stress states in adhesive bond line for various test specimen geometries

	Al/GFRP	Al/GFRP	Al/Steel	Al/Steel	Component Analysis
Outer OD (in.)	12.875	12.5	8	8.625	-
Outer ID (in.)	11.875	11.5	7.834	7.625	-
Inner OD (in.)	11.25	11.25	7.5	7.5	-
Inner ID (in.)	11	11	7	7	-
Bond line thickness (in.)	0.3125	0.125	0.167	0.0625	-
Infusion Resin Stress at -54°C Due to CTE Mismatch					
Hoop Stress (psi)	2961	2866	2951	2845	2888
Axial Stress (psi)	2826	2808	2835	2796	2879
Radial Stress (psi)	120	15	76	-27	7

While each design produces a similar stress state in the adhesive bond line, validation test units were produced with an aluminum outer ring of 12.5" OD and 11.5" ID and a GFRP inner ring. Each test unit is 4" long axially as that provides enough length to reduce the impact of edge effects in the center of the length. The test units are instrumented with two strain gages 180° apart that are monitored during the cool down to sense if they can detect the release of strain energy when the bond line cracks. The test units are cooled slowly to maintain isothermal conditions at a rate of 0.25°C/min and Type K thermocouples are attached to both the aluminum and composite to record the temperature (Fig. 5).

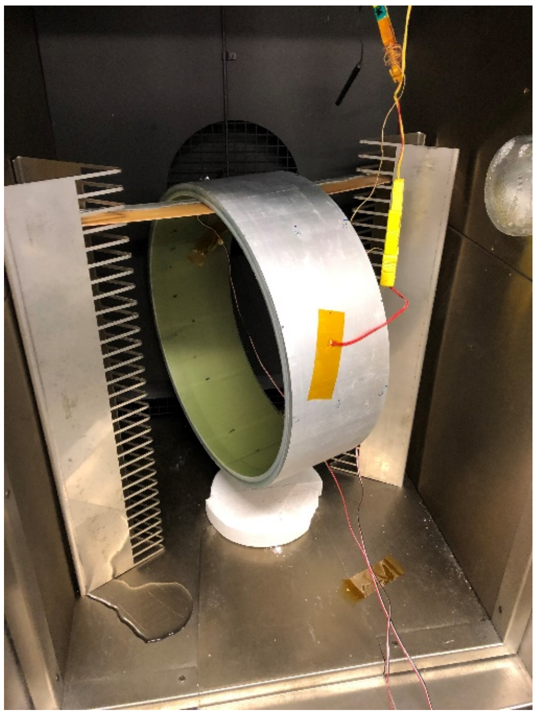

Fig. 5: Test setup inside environmental chamber with thermocouples and strain gages

The first step in the validation testing is to prove that the bond line cracking can be reproduced. A test unit was prepared with the original INF114/251HT infusion resin and cooled to -54°C, held for an hour, and ramped back to room temperature. As shown in Fig. 6 cracking did occur and from the strain gage signal it appeared to occur at around -46°C (Fig. 7).

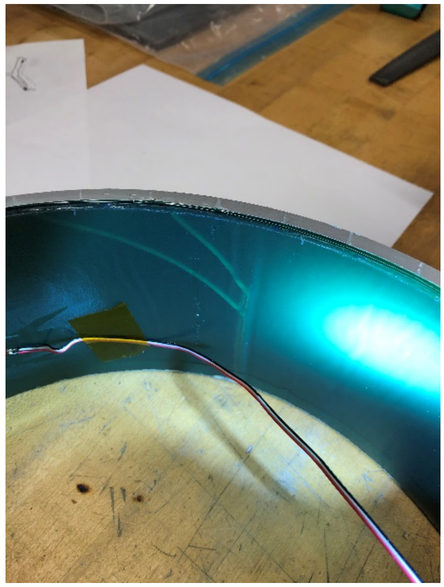

Fig. 6: Bond line cracking with original infusion resin in validation test

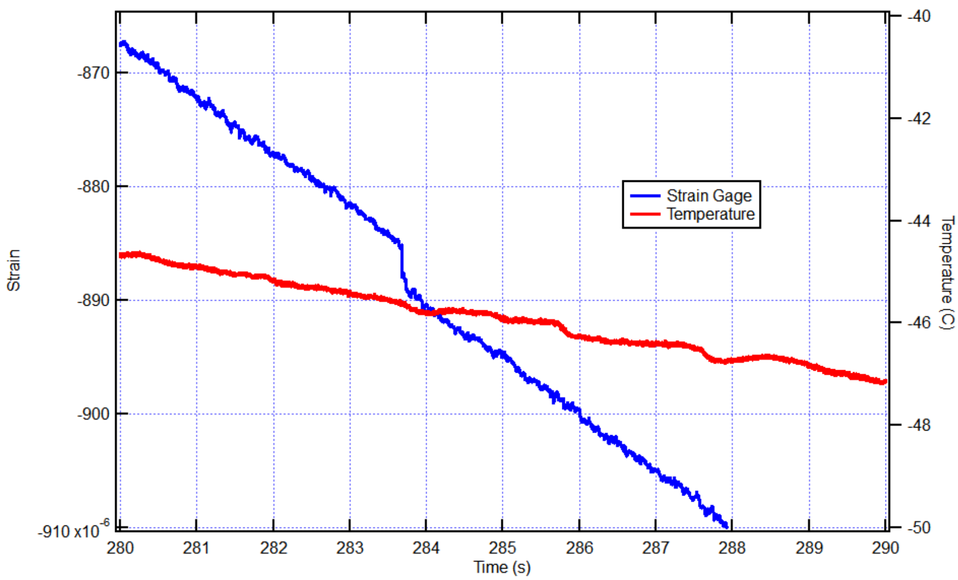

Fig. 7: Strain gage disturbance at approximately -46°C

Additional rings infused with the replacement ANA resin were tested similarly and they did not show any signs of failure. In an attempt to determine the margin gained by the material change, one ring was cooled down to -130°C and no cracking was observed. This is understandable as the ductility of the new resin at -54°C was almost 5x that of the initial infusion resin and a ΔT from the stress free temperature of the bonded joint cannot be achieved.

CONCLUSION

Thermal stresses are a major concern for any bonded interface where the CTE of the adherends differs greatly from that of the adhesive. By measuring the ductility of potential adhesives at the temperature of interest, its likelihood of cracking and failure can be inferred. Additional validation testing is necessary with the proper boundary conditions to reproduce the correct stress state in the actual joint to ensure that the redesign can maintain structural integrity over its service temperature range. While not described in this study, additional testing is also necessary to ensure that the new adhesive can form an adequate bond with its adherends over a similar temperature range.

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