Thermo-mechanical de-bonding of composite-titanium single-lap adhesive joints

A S Ganapathi[a], S Vijay Shankar[b], I Sridhar[a,b], Charles Ng[c]
[a]Rolls-Royce@NTU Corporate Laboratory, Nanyang Technological University, Singapore 639798, Singapore
[b]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore
[c]Rolls-Royce Singapore Pte Ltd, 1 Seletar Aerospace Crescent, Singapore 797565, Singapore

Keywords: Bonded joints, De-bonding, CFRP, Titanium, Adhesive.

ABSTRACT

The aim of this work is to isolate the constituent adherends of the adhesively bonded single lap joints with minimal or no damage to them and prepare the debonded surfaces for re-bonding. Thermo-mechanical separation of carbon fiber reinforced plastics bonded to titanium using a structural adhesive was investigated at four different temperatures. The peak failure load decreases with increase in temperature and a linear softening of the adhesives was observed. Failure modes of the joint were progressed from composite adherend failure to adhesion failure with increase in temperature. There was a permanent deformation of titanium adherend found in the event of adhesion failure of the joint in the temperature region of 135-142 °C. The surfaces of the adherends de-bonded between 135-142 °C were cleaned and re-bonded with the original adhesive. The average lap shear strength of the re-bonded joints is reduced by 5-8% due to the minimal residual traces found on the cleaned surfaces of composite adherends and the initial bending imposed by the permanently deformed titanium adherends.

1 INTRODUCTION

Adhesively bonded joints are preferred over mechanical fasteners to join primary structural members due to their excellent load transfer, joint strength and weight advantages [1]. There is an increased demand to de-bond the assemblies for repair and replacement purposes without damaging the adherends [2]. There are competing research in active and passive polymer adhesive de-bond on demand methods [3-7]. These methods either require modifying the adhesive formulation or to use active supporting layers (primers, scrim, etc.) that significantly affect the mechanical characteristics of the joints. Mechanical destruction is one of the major methods used for de-bonding. This technique may be used in combination with thermal degradation or cutting of the adhesive for easy removal, which may potentially damage the adherends [8]. Bonded joints could be separated with ease by applying a pulling force (peeling) normal to the interface. However, applying a normal tensile load on thin adherends will either distort or damage the surfaces that affect their reusability. Alternatively, a tensile shear load could be applied to the adhesive interface with suitable loading fixtures to separate the adherends.

Tensile shear debonding could damage the adherends due to the superior shear strength of the adhesives at room temperatures. Instead, the mechanical strength of the cured adhesives deteriorates as the temperature increases. This characteristic feature of the epoxy adhesives could be effectively utilized to separate the adherends. However, considerable attention must be given to limit the heating temperature near or below the glass transition temperature (T_g) of the composite adherends.

In this work, a unidirectional composite-titanium single lap joint was investigated for de-bonding ability as a function of temperatures. The separated adherends were re-bonded to examine the effect of de-bonding load and surface cleaning on the lap shear strength. The outcomes are discussed in the following sections.

2 MATERIALS

The hybrid single lap joints (SLJ) were manufactured from carbon fiber-reinforced polymer (CFRP) and titanium alloy adherends bonded to each other with 3M Scotch Weld™ film (a modified thermosetting epoxy) adhesives. CFRP laminates were made from commercially available toughened epoxy unidirectional carbon fiber prepregs.

To fabricate the composite laminate, plies of prepregs were hand-laid and cured by using manufacturer specified cure cycle to obtain a unidirectional lay-up of 4.00±0.05 mm nominal thickness. To obtain better quality composites and prevent warping/thermal induced stresses, the laminates were cooled inside the autoclave chamber to room temperature. The cured laminate and titanium block were cut into specimens as per ASTM D5868-01.
Prior to bonding the surface of the composite and titanium adherends were sand-blasted with 80 grit size brown fused alumina particles and degreased with acetone. An average surface roughness between 4.1 and 5.7 μm Ra was measured on the titanium and composite adherend surfaces. Eventually, the single lap composite-titanium joint with an overlap length as specified in ASTM D5868-01 was fabricated with suitable mould and cure temperature as per the adhesive manufacturer specification. Prior to testing, the specimens were balanced with woven (8 harness weave) glass fibre reinforced polymer (GFRP) end alignment tabs using cyano-acrylic adhesives. This was to ensure a correct load path to the joints and to avoid slipping and damage of unidirectional composites due to gripping pressure.

3 TEST PROCEDURES

The joints were subjected to uniaxial tensile loading in Instron Universal Testing Machine 5569 under displacement control of 1 mm/min with a 50kN load cell. The experimental set up with associated instrumentation is shown in Figure 1.

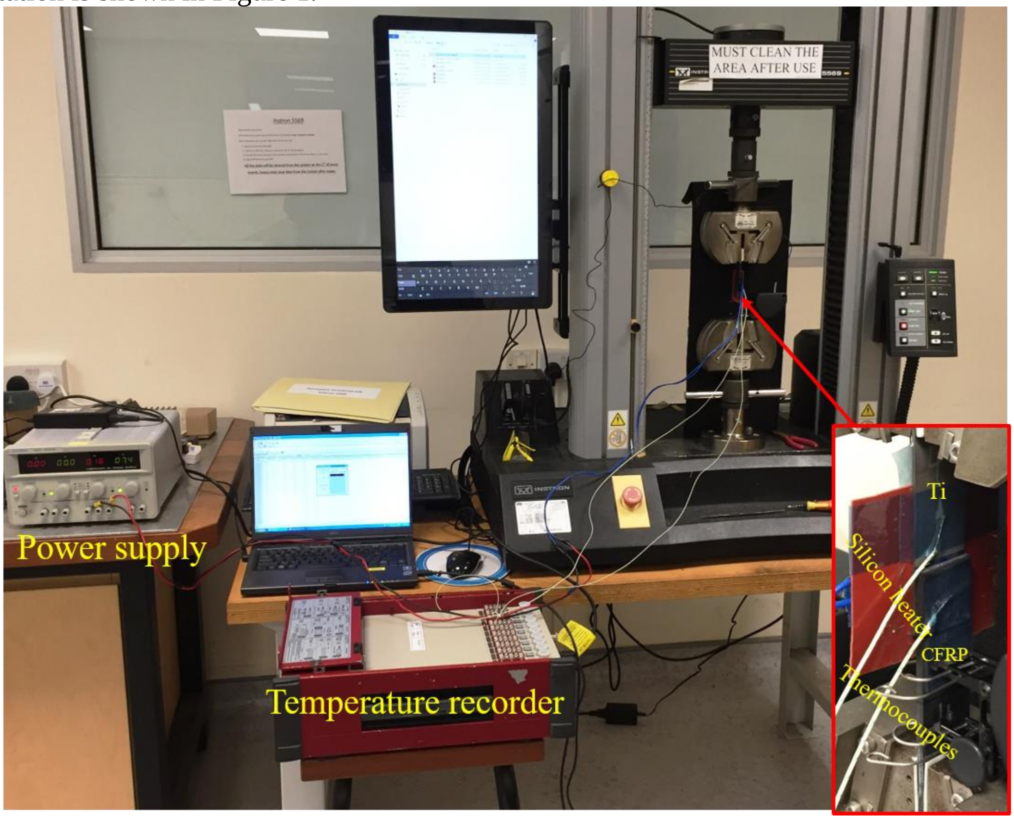


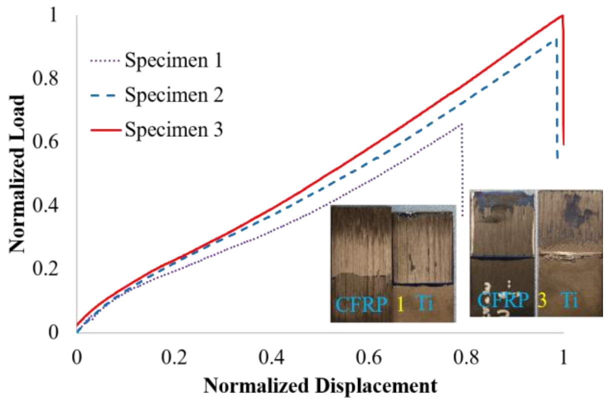
Figure 1: De-bonding test set up for single lap CFRP-Ti adhesive joints

Flexible silicon heaters operated by a power supply unit were bonded on the titanium surface to locally heat the adhesive joints. Two thermocouples were fixed on the Ti and composite surfaces to measure and maintain the steady state temperature of interest (inset in Figure 1). Once the steady state temperature was reached on the adherend surfaces, the joints were subjected to tensile pulling until the joint failed (inherent to the SLJ, the interlap length subjected to a combination of tension and bending forces). The lap shear specimens were tested at four different temperatures in the range of 20ºC and 150ºC (T1, T2, T3 and T4) and the load-displacement curves were captured for further analysis. A maximum of three specimens were tested at each temperature category except for T3, for which only two specimens were tested.

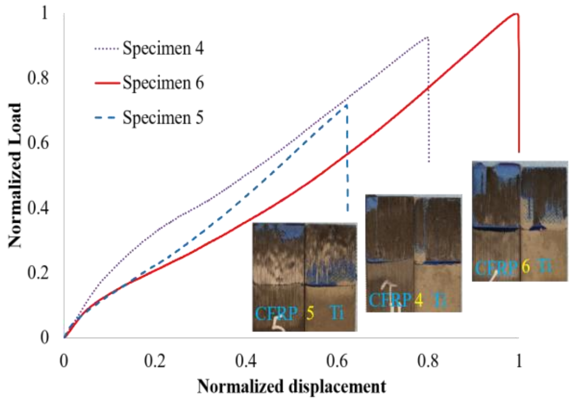
4 RESULTS AND DISCUSSION

4.1 DE-BONDING STRENGTH

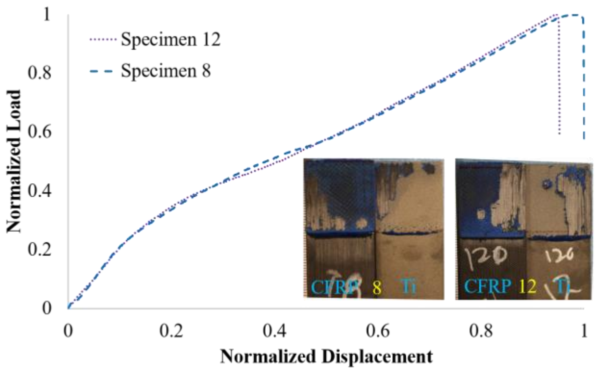
The load-displacement trend of single lap CFRP-Ti joints at different temperatures are as shown in Figure 2 with the failed adherends/adhesives as inset figures. At T1, the average peak load obtained is in the range of 14-17 kN where all the three specimens show CFRP adherend failure as shown in Figure 2(a). A minimal adhesion failure near the bonding edges was found at T2 with an average peak load of 15-17 kN. This means that there was no significant difference in peak load observed at T2 and T1. However, there was a change in extension of joints due to the softening of adhesives as shown in Figure 2(b). Further increase in the temperature to T3 weakened the titanium-adhesive interface and promoted adhesion failure with an average peak load of 9-11 kN. The final failure of all three specimens was a mixed adhesion and adherend failure as shown in Figure 2(c). Eventually, the specimens were tested at T4, the highest temperature in the range, which was below the glass transition temperature (T_g) of CFRP adherends (138 to 150 °C measured by Dynamic Mechanical Aanalyser) and slightly higher than the T_g of 3M Scotch Weld™ film adhesives (~128 °C measured by Differential Scanning Calorimetry). This attributed to a predominant adhesion failure between the adhesive and titanium interface with minimal traces of adherend and adhesives as shown in Figure 2(d). Variations in peak load were observed because of different failure modes of all three specimens tested and the average peak load to fail the joint was in the range of 5-6 kN. In all four temperature cases, there is a permanent deformation of titanium adherends found due to the stiffness mismatch with composite adherends.



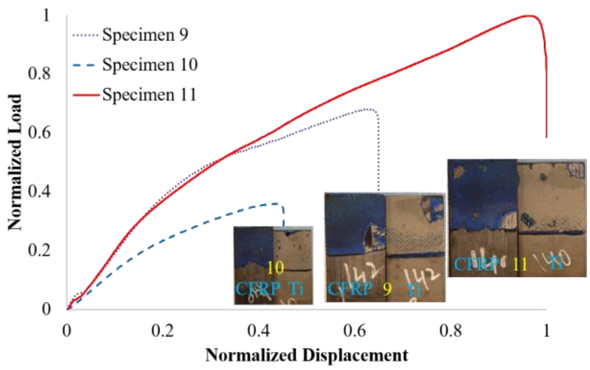
(a) T1 °C



(b) T2 °C



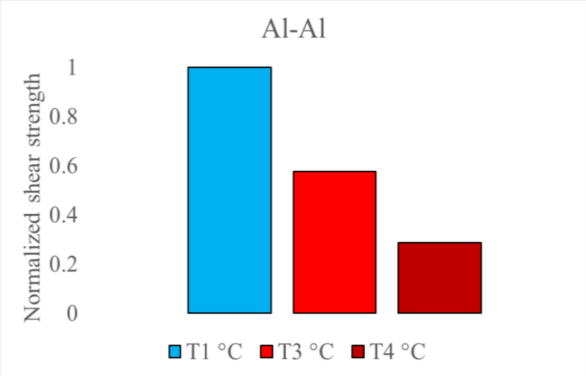
(c) T3 °C



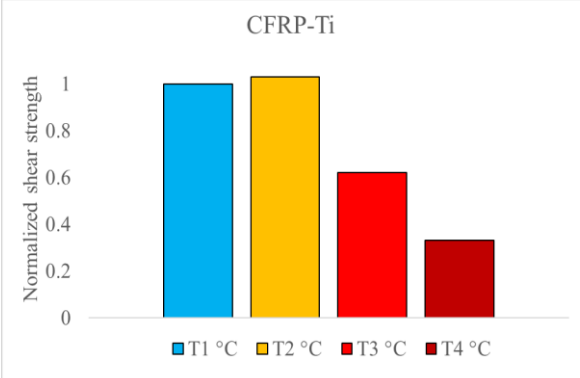
(d) T4 °C

Figure 2: Load-displacement curve of single lap shear tension test at different temperatures

The effect of temperature on lap shear strength of homogeneous aluminium adherend bonded using 3M Scotch Weld™ film adhesive is shown in Figure 3(a) for a comparative study. The maximum shear strength obtained at the lowest temperature tested, T1, was in the range of 40-42 MPa. At elevated temperatures, the shear strength diminished to 23-25 MPa at T3 and 11-13 MPa at T4 due to the softening of adhesives at near T_g temperatures. The shear strength of CFRP-Ti single lap joint at room temperature was found to be in the range of 24-26 MPa, as shown in Figure 3(b), due to the nonhomogeneous nature of the adherends. Interestingly, the shear strength of the CFRP-Ti joint at T2 is slightly higher (~2.5%) than T1. The reason might be the improved ductility of adhesives that promotes a large shear strain bearing capability. However, at elevated temperatures the shear strength was found to be decreased, for example, 14-16 MPa at T3 and 7-9 MPa at T4.



(a)



(b)

Figure 3: Average shear strength ratio of (a) Al-Al (b) CFRP-Ti joints.

4.2 FAILURE ANALYSIS

The stiffness imbalance between titanium and composites adherends attributed to the bending of titanium substrates on the application of tensile loads. This increased the peel stress on the composite surfaces which was bonded to the adhesive. It was noticed at T1, the peel strength of the adhesive was higher than the interface peel strength of composites and contributed to the failure of CFRP layers as shown in Figure 4. The failure initiated at the titanium lap end and propagated towards the composite adherend lap end. From the thickness measurement of CFRP deposited on titanium substrates (~0.23mm), a first ply failure of composite adherend was well established. As the temperature of the adhesive joint was increased to T2, a combination of the dominant adherend and minimal adhesion failure was observed, which indicated that the adhesive strength deteriorated with increase in localized joint temperature. Further increase in joint temperature to T3 enhanced the adhesion failure by weakening the titanium-adhesive interface peel and shear strength, which leads to a combination of dominant adhesion and minimal adherend failure.

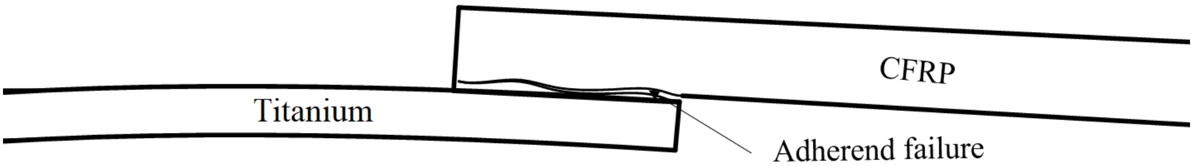


Figure 4: Failure mechanism in CFRP adherend

The failure surfaces of adherends de-bonded at T4 is shown in Figure 5. A predominant adhesion failure at the titanium-adhesive interface was evident. There are traces of CFRP (~0.27 mm) and adhesives noticed on the titanium surfaces as shown in the photographic images of Figure 5. With the help of image processing, the area of residual traces was measured to be 20% for specimen 9, 15% for specimen 10 and 18% for specimen 11. Among the three, specimen 10 shows a minimal peak load due to poor adhesion strength of the joint. Though the peak load required to de-bond the substrates are minimum compared to other debonding temperatures, permanent deformation of the titanium adherends was noticed due to the stiffness mismatch of the adherends.

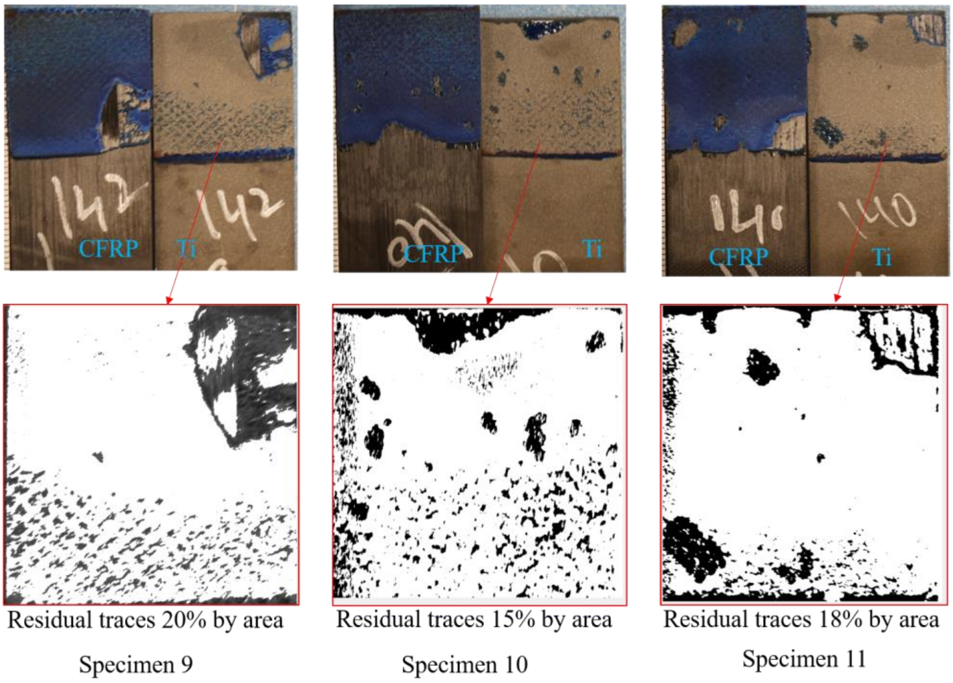


Figure 5: Failure surfaces of adherends deboned at T4

4.3 SURFACE PREPARATION OF DE-BONDED ADHERENDS

The adherends de-bonded at T4 has shown minimal or no damage to the composite adherends, which could be salvaged and reused. The de-bonded titanium surfaces were soaked in acetone for 6 hours to remove the adherend and adhesive remains as shown in Figure 6. Consequently, the plates were sandblasted by using 80 grit size particles and degreased with acetone.

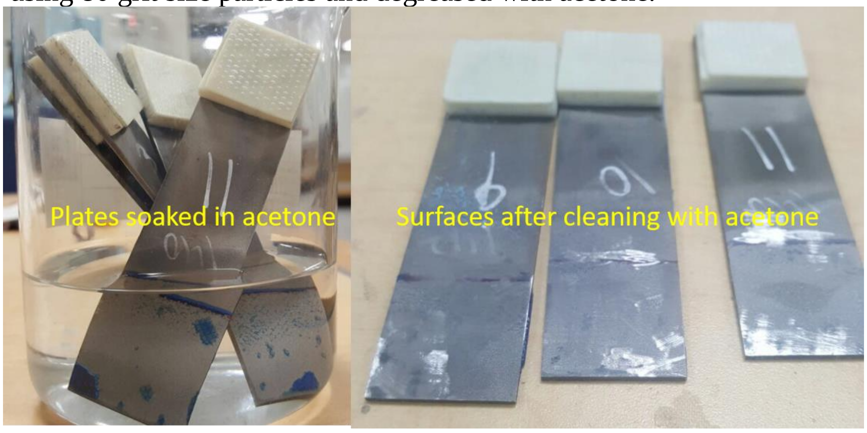


Figure 6: Surface preparation of Ti for re-bonding

There is no suitable method available to clean the composite surfaces without losing the adherend thickness. Nevertheless, the adhesive layers on the CFRP adherend were removed by using an abrasive grinding hand tool followed by manual sanding using 320µ grit papers. This method might be suitable for smaller bonding areas. However, for large bonding areas automated abrasion methods in combination with controlled temperature can be used. Micrographs of the cleaned CFRP surface are shown in Figure 7. Careful attention was given to avoid any loss to composite layers, though there were minor traces of adhesives left on the adherend surfaces.

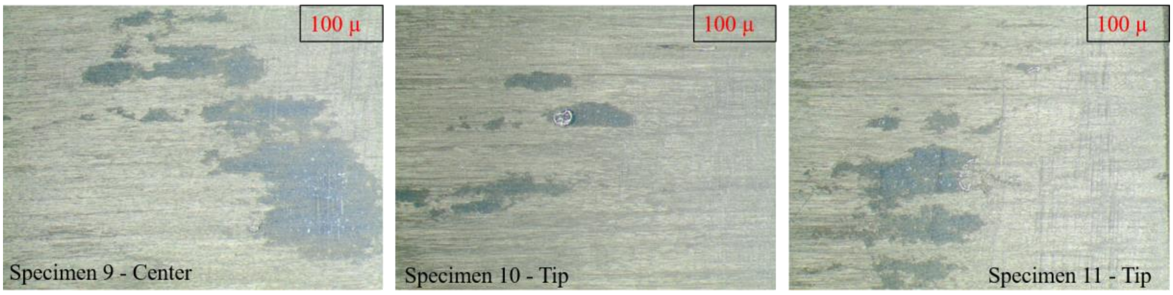


Figure 7: Micrographs of cleaned CFRP surfaces

4.4 RE-BONDING STRENGTH

The adherends de-bonded at T4 were cleaned as explained above and then re-bonded with 3M Scotch Weld™ film adhesive, which is illustrated in Figure 8. The re-bonded joints were prepared by replicating the joint preparation methodology for pristine samples. Though a pressure higher than 0.25 MPa was applied, the titanium substrates were not relieved from permanent deformation that imposed during de-bonding. The deformation in specimen 11 is severe compared to the other two specimens (9 and 10) due to higher peak loads involved. This has contributed to a free bending of the re-bonded single lap shear specimens and attributed to poor bonded regions near the composite edges as shown in Figure 8. This could have been avoided by replacing deformed Ti alloy adherend with pristine substrate to achieve the higher re-bonding shear strength of joints.

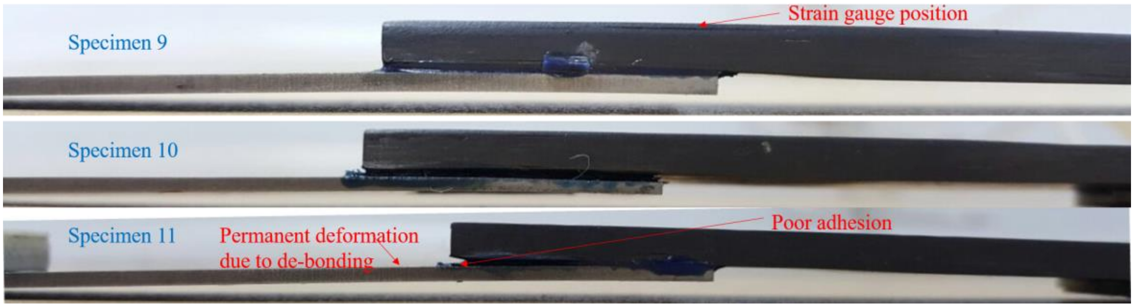


Figure 8: Re-bonded CFRP-Ti adhesive joints

There was no explicit deformation found in composite adherends. A strain gauge was fixed on the bond free surface of the composite adherend as depicted in Figure 8 which is used to measure the change in stiffness. The re-bonded adherends were tested at T1 and the average peak failure load was obtained in the range of 14-16 kN. All the three joints reported a composite adherend failure as shown in Figure 9 which is similar to the pristine joints that were tested at T1.

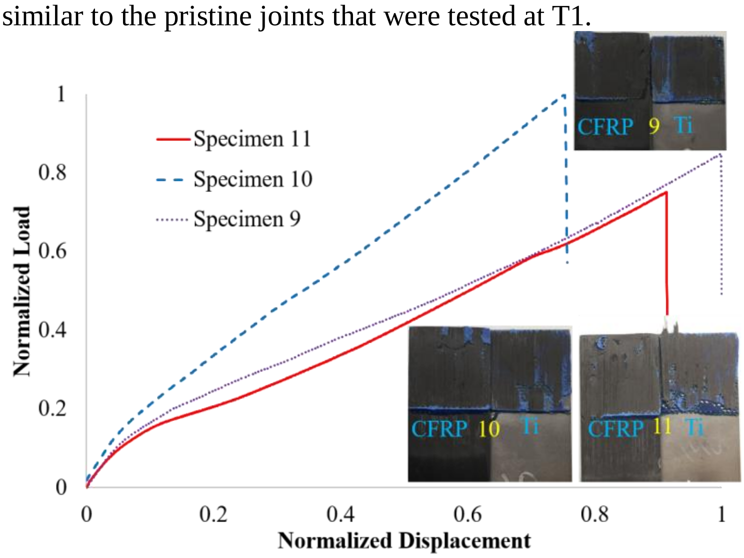


Figure 9: Load-displacement curve of re-bonded CFRP-Ti single lap joints.

A compressive strain was observed on the strain gauge fixed to the composite adherends as shown in Figure 10. The permanent deformation of de-bonded titanium adherend and the stiffness imbalance resulted in the outward bending of the composite adherends, which promoted the pre-matured failure of re-bonded joints compared to the pristine joints. There is approximately a 7% drop in re-bonding strength as compared to the pristine CFRP-Ti joint as shown in Figure 11. The minute adhesive traces found on the CFRP surfaces and the bonding anomalies originated by permanent deformation of the Ti adherends leads to the deterioration of the lap joint shear strength.

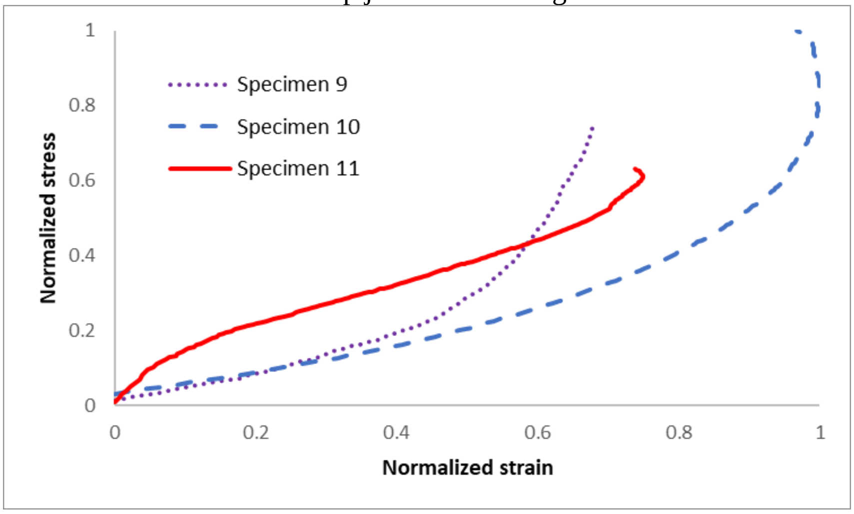


Figure 10: Nominal stress – compressive strain curve of re-bonded CFRP adherends

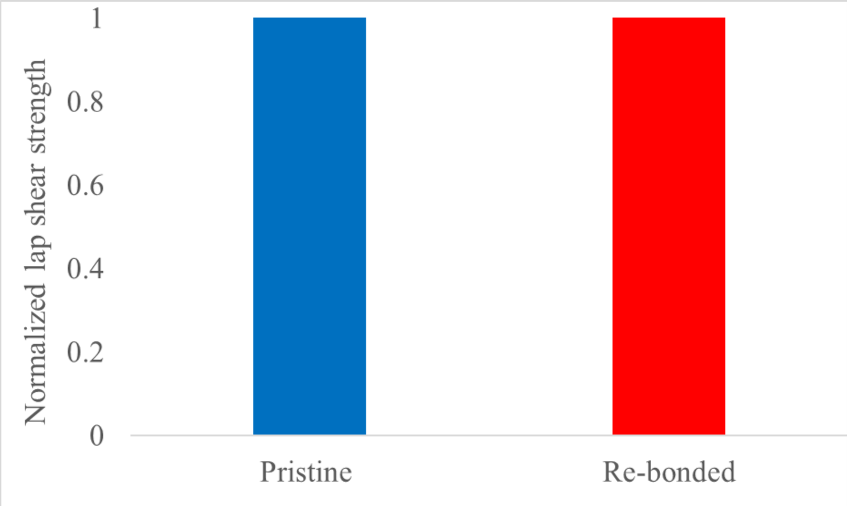


Figure 11: Lap shear strength of CFRP-Ti joint before and after re-bonding.

5 CONCLUSIONS

The effect of temperature on the de-bonding strength of CFRP-Ti adherends was investigated. At temperatures, well below the T_g of adhesives, a composite adherend failure was observed due to the increased peel stresses on the extreme layers that were bonded to the adhesives. The failure of the joint transforms from adherend to adhesion failure as the temperature approaches to T_g of the adhesives. At T4, the strength of the joint decreases due to softening of the adhesive and a predominant adhesion failure with minimal cohesion/adherend failure was observed. The reusability of the de-bonded adherends was examined by re-bonding them with the same adhesive and testing at T1. Curvature found in the titanium adherend contributed to premature failure (approximately 7%) of the joint. It can be concluded that the restoration of thin titanium adherends severely affected the shear strength of structural epoxy adhesives even at near T_g temperatures. Nevertheless, the composite adherends could be restored and re-bonded with pristine titanium substrates to avoid/minimize the loss in stiffness. Great care must be taken to prepare the composite surfaces for re-bonding.

ACKNOWLEDGEMENTS

The authors thank Bhrami Jegatheeswaram Pillai from Rolls-Royce for her contributions and financial support from the National Research Foundation, Singapore and Rolls-Royce Singapore funded Rolls-Royce@NTU Corporate Laboratory through the project MRT 3.3. Assoc. Prof I. Sridhar further thanks School of Mechanical and Aerospace Eng, NTU for the financial support in the form of Research Incentive grant 2016.

REFERENCES

1. da Silva, L.F.M., Ochsner, A. and Adams, R.D., *Handbook of Adhesion Technology*. Vol. 2. 2011: Springer.
2. Concord, A., *De-bonding technologies for adhesivley bonded structures*, in *Faculty of Mathematics, Natural Sciences and Computer Science*. M.Sc. Dissertation Report, 2012, The Brandenburg Technical University Cottbus: Germany.
3. Banea, M.D., da Silva, L.F.M and Campilho, R., *An overview of the technologies for adhesive debonding on command.* Welding equipment and technology, 2013. **24**: p. 11-13.
4. Aubert, J.H., *Thermally removable epoxy adhesives incorporating thermally reversible diels-alder adducts.* The Journal of Adhesion, 2003. **79**(6): p. 609-616.
5. Banea, M.D., et al., *Smart Adhesive Joints: An Overview of Recent Developments.* The Journal of Adhesion, 2013. **90**(1): p. 16-40.
6. Hutchinson, A., Liu, Y. and Lu, Y., *Overview of disbonding technologies for adhesive bonded joints.* The Journal of Adhesion, 2016: p. 1-19.
7. Leijonmarck, S., *Electrically induced adhesive debonding*, in *School of Chemical Science and Engineering*. Licentiate thesis. 2010, KTH: Stockholm.
8. Boschet, D.B. et al., *Method of hot peeling for removing a blade leading edge cap*, US patent, US6578265B2, 2003, United states.