Effect of residual epoxy on single lap joints performance

Srinivasan, Dharun Vadugappatty; Aggarwal, Atin; Idapalapati, Sridhar; Ng, Charles

2020

Srinivasan, D. V., Aggarwal, A., Idapalapati, S., & Ng, C. (2020). Effect of residual epoxy on single lap joints performance. *The Journal of Adhesion*, 96(10), 883-901. doi: 10.1080/00218464.2018.1538878

<https://hdl.handle.net/10356/144180>

<https://doi.org/10.1080/00218464.2018.1538878>

This is an Accepted Manuscript of an article published by Taylor & Francis in *The Journal of Adhesion* on 29 Oct 2018, available online:

<http://www.tandfonline.com/10.1080/00218464.2018.1538878>

Downloaded on 26 Apr 2023 19:05:48 SGT

Effect of Residual Epoxy on Single Lap Joints Performance

V. S. Dharun, A. Atin, I. Sridhar^{1×}

Rolls-Royce@NTU Corporate Laboratory, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.

Charles Ng

Rolls-Royce Singapore Pte Ltd, 1 Seletar Aerospace Crescent, Singapore 79756, Singapore.

ABSTRACT

Design for remanufacturing of adhesively bonded composite structure emphasizes the product features such as ease of disassembly, surface reconditioning, reassembly and validating the structural integrity of rebonded joints. After disassembly of bonded joints, the adhesive on the adherend surfaces should be removed for reassembly. Some part of adhesives will be left over in complex, undulated bonding surface and this residual adhesive may affect the reassembled joint mechanical performance. In this experimental work, two different adherends namely aluminium (Al) and glass fibre reinforced polymer (GFRP) were bonded with 3M DP490 epoxy adhesive and the joint shear strength was determined by tensile single lap shear testing. Further, joints with induced residual epoxy were fabricated and the effect of different percentage of residual epoxy on joint shear strength was investigated. The test result shows that there was no significant reduction in lap shear strength of both GFRP and Al alloy joints. There was no evidence of failure at the residual-fresh epoxy interface that shows good mechanical compatibility between the residual and fresh epoxy. Furthermore, the surface profile measurements of materials surfaces were studied and the residual epoxy surface texture ensures proper mechanical anchoring with fresh epoxy.

Keywords: surface reconditioning, thick adhesive joints, residual epoxy, single lap shear strength and composites repair

[×] Corresponding author: msridhar@ntu.edu.sg

1 INTRODUCTION

Primary aerospace structures are adhesively bonded and have been used for several decades as an alternative to mechanical fasteners such as rivets and bolts. The light weight structures are generally bonded with thermoset epoxy adhesives to meet the desired load bearing requirements and environmental conditions.. A range of physical and chemical phenomenon contribute to adhesive bonding as shown in **Figure 1** [1]. Mechanical abrasion or chemical etching increases the surface roughness, wettability and removes undesirable surface impurities, thereby improving the bond strength provided the adhesive has good chemical compatibility with the adherend material [2]. It is to be noted that there is an optimal surface roughness beyond which the interface bond strength decreases due to insufficient adhesive flow. [2].

Adhesive joint strength depends on the joint geometric parameters (bond line thickness, adherend thickness, overlap length), material properties (adhesive type, adherend), environment conditions (pre-bonding and post-bonding), manufacturing methods and surface preparation techniques [3]. Stress based analytical models explain the distribution of shear and peel stresses along the overlap length considering the bending effects of adherends [4, 5]. The failure of the lap shear joint is due to the combination of shear, peel, cleavage or cohesive failure mechanisms. The through-bond-line-thickness peel stress which is maximum at the edge of overlap length plays an important role in the bond strength [6, 7]. . This would delaminate the composite laminae under transverse tension which leads to failure below the design load [8]. It is to be noted that thinner bond lines give higher shear strength and thicker bondline increases the peel stress due to increased load eccentricity at the joint [9,10]. Apart from joint parameters, surface preparation and functionalization methods (for ex. mechanical, chemical, UV, laser and plasma techniques) also influence the bond strength [11]. The local

adhesive thickness and energy dissipation increases with profile depth and average mean spacing of surface texture profiles that improve the bond strength. The greater mechanical interlocking with the adhesive is achieved with higher negative skewness of the profile. [12]. Jiann Haur et al [13] have shown that the interlaminar failure occurs at $\pm 45^\circ$ layers in thick composite adherends with 5.1 mm of bond line thickness. Their experimental results reveal that each bond is unique and should be designed carefully to maximize the load carrying capacity of the joints.

Adhesive joints should be able to disbond during repair and reassembly [14, 15, 16] processes. As remanufacturing of products has greater impact on economics, environment and society, it is required to improve inspectability and repair the damaged product to the required performance quality. Disassembly and re-manufacturability metrics are used to measure the design features of the product that allow remanufacturing [17]. After disassembling the composite parts, the next requirement is to reassemble a new part by bonding it to the salvaged composite part. Hence, the surface of the salvaged part needs to be reconditioned for rebonding like removing the leftover or “residual epoxy”.

The removal of this residual epoxy requires surface reconditioning or sanding using different precision machining tools and should be carried out without damaging the underlying composite layers. The damage can be avoided by retaining small amounts of epoxy or adhesive on the debonded surface especially at critical locations, so the surface-reconditioning time and associated costs can be reduced. As an alternative solution, fresh epoxy may be applied over the residual epoxy surface and the new part could be reassembled. Hence in this work, the residual epoxies were simulated with different percentages and their single lap shear strengths were measured to compare with pristine samples. The failure analysis of the joints was coupled

with surface preparation parameters to explain the underlying mechanisms of adhesive bonding.

2 MATERIALS

Aluminium alloy 6160 and glass fibre reinforced composites were used to fabricate the single lap shear joints. Glass/epoxy composite laminate was manufactured using the Hexply® M56/37%/7781 prepreg supplied by Hexcel Ltd. The E-glass prepreg is an 8 harness satin (8HS) weave with a fibre volume fraction of 0.45, weight 300 g/m², and cured ply thickness of approximately 0.263 mm. The prepegs were vacuum debulked for 5 minutes after every 4 layers to remove any trapped air during layup for fabricating the monolithic laminate with best quality. The rounded edges of debulked prepegs were cut away after final compaction to reopen the air paths while curing. As the high-performance resin system was specially developed for out-of-autoclave curing, it was cured with recommended vacuum and dwell temperature of 180°C for 120 minutes [18]. The laminate lay-up sequence was unidirectional (0°). 3M scotch-weld DP490 epoxy adhesive was supplied by 3M and used for fabricating the joints. The constituent properties of the material systems are given in **Table 1** [17,20].

2.1 Preparation of adherends

The fabricated GFRP panel was cut into specimens of size 100 mm x 25 mm using water cooled, diamond tipped rotary cutter. The adherends were washed and oven-dried at 60°C for an hour. The composite surface is referred as ‘untreated’ at this stage. The specimens were sand blasted with white alumina media, grit size of 150 and at 0.14 MPa air pressure. The specimens were cleaned with tap water and dried again at 60°C for an hour. The DP490 adhesive was applied followed by acetone wiping with lint free cloth.

The 5mm thick Al alloy sheet was cut into 100 mm x 25 mm specimens using band saw, sand blasted with the same media at 0.2 MPa air pressure. They were cleaned with tap water and oven-dried at 60°C for an hour. The sandblasted Al alloy adherends were treated with surface pre-treatment chemical AC130-2 also known as sol-gel treatment, as recommended by 3M® [19]. Finally, EW5005, which is an epoxy based structural adhesive primer, was applied over sol-gel treated surface [20].

2.2 Adhesive bonding

The two parts (base and accelerator) of the 3M Scotch-Weld DP490 adhesive were mixed in a planetary mixer for 1 minute at 1500 rpm. The well mixed adhesive was applied over the conditioned adherend surfaces which were placed carefully in a mould to ensure proper alignment. The adhesive joint was cured for 24 hours at room temperature, followed by 2 hours at 65°C [21]. The bond line thickness was maintained in the test samples with the help of shims. It was difficult to achieve a uniform bond line thickness across the entire overlap length and was found to vary between 1.6 mm to 3.1 mm. End tabs and alignment tabs were bonded to the joints to avoid bending and adherend failure at the grips due to clamping pressure.

2.3 Residual epoxy samples preparation

The DP490 epoxy was applied to one of the conditioned adherend surface (Figure 2a) and cured (Figure 2b) as described above. These samples shall be referred to as “residual epoxy samples”. The residual epoxy samples were subjected to a temperature of 90°C for 30 minutes. Thus the actual debonding process condition was simulated where the epoxy is subjected to 90°C. Then, the residual epoxy surface was abraded with sand paper of grit size number 320 to reduce the amount of residual epoxy and achieve different percentages (Figure 2c). After cleaning the sanded surfaces with acetone, a fresh layer of epoxy was

applied on the surface (Figure 2d) and the adhesive joints were cured. This resembles the actual reassembly process. Different configurations of residual epoxies including random configuration were obtained for studying their effect on the rebonding strength as shown in **Figure 3**. The thickness of the residual epoxy layer was not accurately controlled as there were variations in bond line thickness due to uneven bond surface of actual structures.

3 EXPERIMENTAL METHODS

3.1 Surface roughness measurements

The surface texture profile of GFRP adherends was measured before and after sandblasting. Likewise, it was measured after different conditioning processes such as sand blasting, sol-gel treatment and primer application. Similarly, the surface texture profile of residual epoxies was quantified to compare with the adherend surface profiles. A Taylor-Hobson precision equipment was equipped with a non-contacting laser profilometer and a conducting gauge, which were used to scan the surface. The pulsed laser with emitted wavelength of 670 nm was used to acquire the profile data over a 5 mm length at the rate of 500 $\mu\text{m/s}$ and spacing of 0.5 μm at random distances. As the untreated GFRP had a reflective surface, the surface profile measurements were taken by induction gauge. Five different sets of values were measured and the average value was reported with variance. The data was levelled and filtered using a high-pass cut-off value of 0.8 by Talyscan 150 software. From the scanned measurement data, the average surface roughness, R_a , the average peak-to-valley height, R_{tm} , the profile depth P_t , kurtosis, R_{ku} and skewness R_{sk} were deduced.

3.2 Scanning electron microscopy (SEM) and optical microscopy

The untreated and sandblasted surfaces of samples were investigated using JEOL JSM-5600LV SEM. Both untreated and sandblasted GFRP samples of size of 23 mm x 12 mm

were stacked to the specimen mount using conducting tape and sputter coated with a thin layer of platinum for 100 s. An accelerating voltage of between 15 and 25 kV, spot size of between 35 μ m and 37 μ m and working distance of 14-15 mm were maintained to capture the images. The failure surfaces of joints were analysed using the Olympus optical microscope at different magnifications.

3.3 Water contact angle measurements

The wettability of adherend surfaces was determined by measuring the water contact angle, known as sessile drop method using dataphysics (model OCA35), optical contact angle measuring and contour analysis systems. A hypodermic syringe was filled with deionized water and the water droplet was formed with dosing volume of 17 μ l at a rate of 20 μ l/s. The contact angle was measured once the droplet reached the equilibrium state. The optical images of deposited drops were captured by high resolution camera with zoom lens and analysed by the software. The contour of the droplet was identified automatically and the angle between the static plane of adherend surface and the concave or convex shape of droplet was measured on both left and right sides. An average of 5 readings with standard deviation has been reported.

3.4 Single lap shear test

The single lap shear tests were carried out in accordance with ASTM D5868 standard for GFRP joints and ASTM D1002 standard for Al alloy joints [22, 23]. GFRP adherends of thickness 8 mm with a reduced overlap length (13 mm) were used in the joint fabrication as shown in **Figure 4a**. Additionally, Al alloy adherends of 5mm thickness were used as shown in **Figure 4b**. This is to reduce the induced peel stress, as discussed in the introduction. The ASTM standard for metallic adherends (D1002) recommends that the test results could be

compared for same thickness adherends in developmental tests. In this work, two thick adherend material systems are considered: (a) joints with long fibre reinforced polymer joints allow to observe possible failure of the plies especially at the adhesive – adherend interfaces, (b) being thick adherend, joints with Al, predict the adhesive behaviour under varying joint parameters with residual epoxies. The design of composite joints was similar to real structures where the joint parameters would vary locally due to surface undulations. These two different design philosophies were considered to estimate the effect of residual epoxies.

All the mechanical tests were conducted at 22°C using a servo-hydraulic MTS Universal Testing Machine under displacement control at a loading rate of 13 mm/min and 1.3 mm/min for GFRP and Al alloy adhesive joints respectively. Knurled grips were used to accommodate the high thickness test samples. The failure load was measured by 50 kN load cell and displacement was measured through cross-head displacement. The ultimate shear strength of the lap joint under tensile loading was obtained by $\tau = P_{\max}/A$, where $P_{\max}$ is the maximum load at failure and A is the interface bond area.

3.5 Digital image processing

The residual epoxy sample images were taken and a MATLAB® code was used to process the images for estimating the percentage of residual epoxy. MATLAB functions were used where the original image was converted into a binary image consisting of black and white areas representing portions with and without adhesive respectively. An appropriate threshold value was given based on which the pixels were converted into either black or white. Finally, the percentage of black portion was calculated against the total area.

4 RESULTS

4.1 Digital image analysis

Figure 5 shows the original image and the converted binary image for a threshold value of 0.3. The percentage of black colour was estimated to be 36.35% after processing the image. **Tables 2** and **3** list the measured residual epoxy values of GFRP and Al alloy single lap joints, respectively.

4.2 Surface morphology and contact angle analysis

The untreated and sandblasted GFRP adherend surfaces were studied through SEM images. The untreated surface was very smooth as the matrix material completely embedded the fibres as shown in **Figure 6a**. **Figure 6b** and **Figure 6c** depict the sandblasted GFRP surface where the fibres were exposed locally in warp and weft directions. The rough matrix surface was visible in other areas.

The sandblasted Al alloy surface is shown in **Figure 6d**. The surface roughness of Al alloy adherend surfaces increased by sandblasting upto 240% and slightly decreased by 24% after solgel treatment process. The surface texture parameters were not affected by the primer application. The profile depth and kurtosis also improved by 271% and 276% respectively after sandblasting, remained same after sol-gel treatment but slightly decreased after applying the primer. The skewness of the sol-gel treated surface was -0.9 and higher than all conditioning process as shown in **Figure 7a**.

The surface profile of residual epoxy DP490 was compared with the primed Al alloy and sandblasted GFRP adherend surface profiles in **Figure 7b**. It shows that the residual epoxy surface has 37% higher surface roughness than conditioned Al alloy surface. The kurtosis was two times higher than both the GFRP and Al alloy surfaces.

The effect of different surface conditioning on wetting the adherend surfaces was characterized by measuring the contact angle and the results are presented in **Figure 8**. The wetting kinetics of Al alloy surface improved after every conditioning process. There was not much difference in the wetting properties of sandblasted GFRP and residual epoxy surface. However, it is difficult to describe the role of wetting kinetics of very high viscous paste adhesives on adhesive bond strength.

4.3 Single lap shear test results

Typical measured tensile load versus displacement response of pristine thick GFRP SLJs, and joints with 50%, 70% and 90% residual epoxy are as shown in **Figure 9a**. It is almost linearly elastic with a sudden drop in load indicating catastrophic failure of the joint and the measured peak load values are 7.46 kN, 5.91 kN, 8.69 kN and 10.19 kN for the composite joints.

Similarly, the tensile load versus displacement curve is depicted for pristine thick Al alloy joints, and joints with 43% and 100% residual epoxy in **Figure 9b**. The initial response is linear and the load dropped gradually after reaching a peak value. The gradual failure could be due low loading rate which allows time for adhesive deformation.

The behaviour of different percentage of residual epoxy samples of GFRP and Al alloy joints was compared and is shown in **Figure 10**. The trend line of GFRP joint results shows that there is no significant reduction in shear strength due to residual epoxies. As the percentage of residual epoxy increases, the shear strength approximately remains same as compared to pristine joints within the experimental scatter. Al alloy joints, on the other hand, had a negative trend line with a slope of 0.036 MPa which implies slight reduction of shear strength in residual epoxy joints. The variance in the strength was due to joint parameters such as overlap length and bond line thickness of joints. **Figure 11a** and **Figure 11b** show

that the lap shear strength decreases as the overlap length and bond line thickness increase. This variation is in accordance with other literature studies, see for example [12].

4.4 Failure mode analysis

The fractured surface micrographs are shown in **Figures 12a and 12b**, respectively for GFRP and Al alloy joints. The failure surface of GFRP joints had adhesive traces and fibres which was a mixed-mode failure. Further, the optical microscopic images of GFRP samples were shown in **Figure 13**. Minor (less than 5%) adhesive spots in both the pristine and residual epoxy failure surfaces show the cohesive failure mode of the joints whereas the ruptured fibres indicate adherend interface damage. The failure surface of sample 4 shows more ruptured fibre as compared to other samples. Furthermore, the broken fibres could be seen over the adhesive surface as shown in **Figure 14**.

Microscopic images of the failed surfaces of adhesives also revealed the presence of tiny voids with diameter of between 30 μm and 70 μm as shown in **Figure 15**. These voids were formed during the adhesive mixing and application process. As this is a high viscous paste adhesive, it was difficult to remove the air bubbles completely before curing.

5 DISCUSSION

5.1 Adhesion modelling approach

The smooth, untreated Al alloy surfaces were blasted with white alumina media because of which the surface roughness increased from 0.8 μm to 2.8 μm . After further treatment with sol-gel etchant, the kurtosis improved. As the valleys of the sol-gel treated surfaces were filled with thin layer of primer, the profile depth and skewness were found to decrease.

The chemical and mechanical characteristics of the GFRP surface were altered by the sandblasting process where some quantity of the matrix was removed and fibres were exposed locally. Sandpaper abraded residual epoxy had higher profile depth, peak to valley height, kurtosis and negative skewness than GFRP and Al alloy surface that helped to achieve proper mechanical anchoring. As the residual epoxy surface has better surface profile when compared to GFRP and Al alloy, it should provide strong mechanical keying to the fresh applied epoxy and the interface was expected to be stronger than other interfaces under tensile shear loading.

5.2 Effect of residual epoxies on GFRP joints

As observed from the SEM micrographs, the GFRP joints have three different interfaces namely local fibre-adhesive interface, matrix-adhesive interface and residual epoxy-adhesive interface. These three interfaces have different failure energies which would contribute to the failure strength of the joint. Although the joints do not have similar ultimate shear load, there is less dispersion in the shear strength data. As the residual epoxy percentage increased, there was no decrease in the single lap shear strength of the GFRP joints. The adhesive bond line thickness, overlap length, manufacturing defects such as voids, difference in the natural adhesive fillets and non-homogenous surface conditioning could be the reason for the slight variance in the joint lap shear strength. The difference in adhesive thickness was not accounted for in the alignment tab thickness after fabricating the joints. The alignment end tabs were provided only for 2 mm thick adherends. If the bond line thickness was different from 2mm, there would be an induced peel stress and the joint would fail under lower load. For example, sample 3 and 12 have the bond line thickness of 3.1 mm and 2.4 mm respectively that were subjected to additional bending moments of 3.35

kNmm and 1.18 kNmm. These samples have lower shear strength of 15.6 MPa and 17.54 MPa among other GFRP SLS test samples.

The failure of pristine and residual epoxy samples was mixed-mode where the adherend-adhesive interface failure was dominant. One of the adherends had very little traces of DP490 epoxy adhesive with fibre rupture whereas the other adherend had broken fibres. The failure surfaces of joints with highest and lowest strength were analysed using optical microscopic images. They show that the lowest strength joint had very less damaged fibres whereas the highest strength joint had more broken or ruptured fibres.

The failure modes of all samples were same irrespective of the presence of residual epoxies. As there was no evidence of failure at the residual epoxy-adhesive interface, the strong boundary layer adhesion between the residual and fresh epoxies could explain the reasons for uniform bond shear strength.

5.3 Effect of residual epoxies on Al joints

There are two interfaces namely adherend-adhesive and residual epoxy-adhesive in the Al alloy joints. The pristine joint had more stiffness when compared to the residual epoxy samples. As the residual epoxy percentage was increased from 0% to 100%, there was slight reduction of 3.6 MPa in the single lap shear strength of the Al alloy joints. But it was due to change in adhesive bond-line thickness and not because of residual epoxies. The difference between the bond line thickness of pristine and residual epoxy samples ranged between 0.5 mm and 0.7 mm.

It should also be noted that the failure mode was mixed-mode and same for all samples. There was no failure at the residual epoxy-adhesive interface. There was very good chemical compatibility between the residual epoxy and fresh epoxies as both have same chemical

composition. The strong chemical bonds provide the required load transferring capacity to the joint. Therefore, the residual epoxy need not have to be completely removed in the composite repair process. A few islands of residual epoxies will not reduce the static strength of the thick joints.

5.4 Re-manufacturability

An adhesively bonded structure which has two composite shells bonded by DP490 adhesive system can be debonded where one of the adherend part salvaged while remanufacturing. As another adherend part was sacrificed, it should be replaced with a new part. The number of ideal parts (IP) is here 2.

Figure 16 illustrates the surface conditioning time required to remove the residual epoxies from the rebonded structure. The adhesive removal rate was higher initially but decreased with time due to increased risk of damaging the debonded composite. For example, the residual epoxy could be removed completely by using multiple tools which would take at least 15 minutes for a bond volume of 150 mm x 100 mm x 2 mm. By leaving 20% residual epoxies, the surface conditioning time would be reduced by 200% and the composite would not be damaged.

The remanufacturability metric of the bonded joint was assessed by cleaning metric (α) where the surface reconditioning process investment in terms of processing time and equipment could be compared for different methods. The usable cleaning score could be easily calculated to compare the remanufacturability metric as other metrics such as damage correction, quality assurance and part interfacing metric will be remaining same. For example, the ‘complete’ removal of residual epoxy process scores 6 (CS, cleaning score) whereas the 80% removal of residual epoxy process scores 3 and the cleaning metric would be improved from 1/3 to 2/3 by eliminating precision surface preparation process.

$$\alpha_{\text{Cleaning (complete)}} = \frac{IP \times 1}{CS} = \frac{2 \times 1}{6} = \frac{1}{3}$$

6 CONCLUSION

As the remanufacturability of specific products depends on surface-reconditioning requirements, the scientific investigation on the effect of residual epoxies in thick adherend joints shear strength was reported in this work. It has been proven that there is no failure at the residual epoxy- fresh adhesive interface in two design philosophies. Very good mechanical anchoring, strong boundary layer adhesion and chemical bonding between the residual-fresh epoxy helps to retain the bond strength similar to that of the pristine samples. This work helps to eliminate the inclusion of multiple delicate sanding or finishing processes for removing residual epoxies in complex, undulated composite surfaces ensuring the initial ply fibres are undamaged.

ACKNOWLEDGEMENTS

This research was carried out in the Rolls-Royce@ NTU Corporate Laboratory at Nanyang Technological University Singapore with support from National Research Foundation (NRF) of Singapore under Corp Lab@University Scheme. Authors thank Mr. Dariusz Dorochoicz (Rolls-Royce Norway) for many helpful discussions. Sridhar acknowledges the research incentive award from the MAE School, NTU Singapore.

REFERENCES

1. Goldschmidt, A.; Streitbeger, HJ (2003) BASF Handbook on Basics of Coating Technology. Berlin:Vincentz.
2. Ebnesajjad, S.; Landrock, A. H., Chapter 1 - Introduction and Adhesion Theories. In Adhesives Technology Handbook (Third Edition), Ebnesajjad, S.; Landrock, A. H., Eds. William Andrew Publishing: Boston, 2015; pp 1-18.
3. Budhe, S.; Banea, M. D.; de Barros, S.; da Silva, L. F. M., An updated review of adhesively bonded joints in composite materials. International Journal of Adhesion and Adhesives 2017, 72, 30-42.
4. Goland, M., The stresses in cemented joints. J. Applied Mechanics, Trans. ASME 1944, 66, A-17-A-27.

5. da Silva, L. F. M.; das Neves, P. J. C.; Adams, R. D.; Spelt, J. K., Analytical models of adhesively bonded joints—Part I: Literature survey. *International Journal of Adhesion and Adhesives* 2009, 29 (3), 319-330.
6. da Silva, L. F. M.; das Neves, P. J. C.; Adams, R. D.; Wang, A.; Spelt, J. K., Analytical models of adhesively bonded joints—Part II: Comparative study. *International Journal of Adhesion and Adhesives* 2009, 29 (3), 331-341.
7. Tomblin, J.; Harter, P.; Seneviratne, W.; Yang, C., Characterization of Bondline Thickness Effects in Adhesive Joints. *Journal of Composites, Technology and Research* 2002, 24(2), 332-344.
8. Ojalvo, I. U.; Eidinoff, H. L., Bond Thickness Effects upon Stresses in Single-Lap Adhesive Joints. *AIAA Journal* 1978, 16 (3), 204-211.
9. Hart-Smith, L., Adhesive Bonding of Composite Structures- Progress to Date and Some Remaining Challenges. *Journal of Composites, Technology and Research* 2002, 24(3):133-151.
10. da Silva, L. F. M.; Rodrigues, T. N. S. S.; Figueiredo, M. A. V.; de Moura, M. F. S. F.; Chousal, J. A. G., Effect of Adhesive Type and Thickness on the Lap Shear Strength. *The Journal of Adhesion* 2006, 82 (11), 1091-1115.
11. Baldan, A., Adhesively-bonded joints and repairs in metallic alloys, polymers and composite materials: Adhesives, adhesion theories and surface pretreatment. *Journal of Materials Science* 2004, 39 (1), 1-49.
12. Tzetzis, D., The role of surface morphology on the strength and failure mode of polymer fibre reinforced single lap joints. *Journal of Materials Science* 2008, 43 (12), 4271-4281.
13. Tang, J. H.; Sridhar, I.; Srikanth, N., Static and fatigue failure analysis of adhesively bonded thick composite single lap joints. *Composites Science and Technology* 2013, 86, 18-25.
14. Banea, M.; Silva, L. F. M.; Campilho, R., An overview of the technologies for adhesive debonding on command. *Annals of the University 'Dunarea de Jos' of Galati: Fascicle XII, Welding Equipment & Technology* 2013; Vol. 24, p 11-14.
15. Hutchinson, A.; Liu, Y.; Lu, Y., Overview of disbonding technologies for adhesive bonded joints. *The Journal of Adhesion* 2017, 93 (10), 737-755.
16. Lu, Y.; Broughton, J.; Winfield, P., A review of innovations in disbonding techniques for repair and recycling of automotive vehicles. *International Journal of Adhesion and Adhesives* 2014, 50, 119-127.
17. Ilgin, M.; Gupta, S., *Remanufacturing Modeling and Analysis*. Boca Raton: CRC Press, 2012.
18. Hexcel, HexPly® M56 180°C (350°F) Out-Of-Autoclave Curing Matrix. Product Data Sheet, 2017.
19. 3M™ Surface Pre-Treatment AC-130-2. Application Guide, https://www.3m.com/3M/en_US/company-us/all-3m-products/~3M-Surface-Pre-Treatment-AC-130-2/?N=5002385+3292667587&rt=rud. Accessed March 2018.
20. 3M Scotch-weld Structural Adhesive Primer EW-5005. Technical Data Sheet, 2018.
21. Scotch-Weld EPX Adhesive DP490. Product Data Sheet, 1996.
22. Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding, 2014.
23. Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal), 2010.

Table 1 Mechanical properties of materials

Material	Tensile modulus (GPa)	Tensile yield strength (MPa)
M56 composite	25	470
Al alloy	70	290
DP490	1.6	31

Table 2 GFRP single lap joint configuration

S.No	Bond line thickness (mm)	Overlap length(mm)	Bond area (mm²)	% of residual epoxy
1	2.5	13.6	340	0
2	2.2	15.1	377.5	0
3	3.1	15.6	390	0
4	1.9	13.1	327.5	90
5	2.2	13	325	86
6	2	13.6	340	70
7	2.9	13.9	347.5	47
8	2	12.9	322.5	69
9	2	13	325	70
10	2	13.4	335	65
11	2	12.3	307.5	66
12	2.4	13.5	337.5	50
13	1.8	13.5	337.5	29
14	2.1	13.1	327.5	36

Table 3 Al alloy single lap joint configuration

S.No	Bond line thickness (mm)	Overlap length(mm)	Bond area (mm²)	% of residual epoxy
1	1.7	12	300	0
2	1.6	13.1	327.5	0
3	2.1	13	325	0
4	2.3	13.4	335	100
5	2.3	13.9	347.5	100
6	2.1	12.6	315	48
7	2.1	13	325	43

8	2.2	13.2	330	43
9	2.3	13.3	332.5	46

Figure 1 Adhesion coating mechanisms to the substrate [1]

Figure 2 Schematic of Residual epoxy sample preparation: (a) prepared adherend surface; (b) cured fresh epoxy; (c) abraded 'b' and (d) fresh epoxy applied over 'c' for bonding with other adherend

Figure 3 GFRP residual epoxy samples

Figure 4 Schematic diagram of SLS joints : (a) GFRP and (b) Al alloy

Figure 5 Percentage of residual epoxy through image processing method

Figure 6 SEM images (a) Untreated GFRP surface; (b) Sandblasted GFRP; (c) Magnified sandblasted GFRP and (d) Sandblasted Al alloy

Figure 7 Surface profile measurements: (a) Al alloy and (b) different material systems

Figure 8 Contact angle of material surfaces

Figure 9 Load versus displacement response of single lap joints: (a) GFRP joints and (b) Al alloy joints

Figure 10 Effect of residual epoxy on joint strength

Figure 11 Effect of joint parameters on joint strength: (a) bond line thickness and (b) overlap length

Figure 12 Failure surface : (a) GFRP joints and (b)Al alloy joints

Figure 13 Failure surface of GFRPs: (a),(b) sample3 and (c) and (d) sample4

Figure 14 Fibre traces on adhesives surface after failure (samples 5 and 10)

Figure 15 Presence of voids in GFRP joints (a) sample 1 and (b) sample 4

Figure 16 Surface reconditioning time after debonding