A parametric study on strength and stiffness of hybrid scarf joints

Sridharan Vijay Shankar, AS Ganapathi and Sridhar Idapalapati
School of Mechanical and Aerospace Engineering, Nanyang Technological University,
50 Nanyang Avenue, Singapore 639798, Singapore

Keywords: Composite adherends, Hybrid scarf joints, Fasteners, Adhesive, Failure

ABSTRACT

This work presents a parametric study of adhesively bonded scarf joints enriched with mechanical fasteners. Tensile tests of two different fastener positions along the load path were carried out and compared with bonded scarf joint. It was found that the hybridised joints could carry significant load post adhesive failure with minimal influence on the stiffness of the structure. On further investigation of fastener position in hybrid joints it was found that when fasteners were placed close to each other (equidistant from the centre), could carry a higher load than the joint with fastener placed near the joint edge. The failure modes for the bonded joints was a partial cohesive failure (special cohesive failure) whereas the failure mode of hybrid joints was a substrate failure (shear out) influenced by the fasteners along the load path and partial cohesive failure on the bonded surface.

1 INTRODUCTION

In composite structural joints when there is a requirement for high strength recovery, homogenous bond stresses and aerodynamically compatible joint, a bonded scarf joint is preferred [1]. Some of the other key advantages of scarf joints over single lap bonded joints are reductions in secondary bending moment and related peel and shear stresses [2, 3], due to flush surface at the joint edge by means of minimized load path and uniform stress distribution. Furthermore, scarf joint configuration can also be used to repair a large section of composite structure [4, 5]. The geometric discontinuity of the adherends results to the weaker section in the bonded region, hence it is very important to assess the structural integrity of the joint section [6].

There have been studies reported in the past, for example, parametric studies on scarf configurations [1, 7], stress analysis across bond length [3, 8] and numerous volumes of research in finite element methods to evaluate scarf joints [9-11]. Whereas hybridization through enrichment of the bonded joint with mechanical fastener has been seldom explored except for from the work of Hart-Smith [12]. The study of hybrid joint is predominantly focused into the single lap bonded joint (SLBJ) [13], notable amount of research works have explored hybridization of SLBJ [12, 14-16], The results suggests that use of ductile adhesives and thick bond line thickness have considerable increase of fracture onset load and have shown potential to outperform bolted joints and bonded joints [15, 17].

Hence, based on the inferences from the literature, the objective of this research work is to study the influence of the mechanical fastener to the scarf joint system. Which is assessed by the joint performance under uniaxial tensile loading for different fastener positions and analysis of the mode of failure.

2 GENERAL SPECIFICATIONS

2.1 MATERIALS AND MANUFACTURING

The scarf joints were manufactured from unidirectional glass fiber-reinforced polymer (GFRP) adherends bonded to each other with 3M Scotch Weld^{TM} film adhesive with a knit scrim carrier. GFRP composite laminates were made from commercially available E-glass fiber epoxy prepregs (G17500). To fabricate the composite laminate, 56 plies of prepregs were hand-laid to obtain a unidirectional lay-up and cured in an autoclave with temperature, pressure and vacuum to obtain

composite laminates of 6.23±0.05 mm nominal thickness. The vacuum bagged mould was maintained at a vacuum pressure of 0.08MPa and the stacked prepregs were cured at 120°C for 2 hours under 0.345MPa pressure. To obtain better quality composites and prevent warping/thermal induced stresses, the laminates were cooled inside the autoclave chamber to room temperature. The quality of laminate was further verified with ultrasonic scanning for the presence porosities and voids post curing.
The scarfing operation was performed with a G-code programmed for a 5º scarf angle input to the 3-axis Mazak CNC machine. The scarf angle was further verified with by measuring the slope length and thickness. The adherends were cut to 25.4 mm width (as per ASTM D3039) with 4 mm (4 flutes) carbide coated end mill cutter.

2.2 DESIGN OF HYBRID JOINT

Joints were prepared after a thorough degreasing of the bonding surface with acetone and drying them prior to the application of a single layer of 3M Scotch Weld^{TM} film adhesive. To manufacture the scarf joints special mould was used to enable precise control of the adherend alignment. The movement of the adherends was contoured during the liquidous stage of the film adhesive with pins and fastened clamping across the width. The mould assembly was autoclave cured for 3 hours as per prescribed curing cycle from the adhesive manufacturer. The average bond-line thickness was measured to be 0.36±0.03 mm. The hybrid joints were manufactured by drilling two 4 mm holes at 20 mm (Hybrid A) and 10mm (Hybrid B) away from bonded edges using a CNC drill as shown in Figure 1.

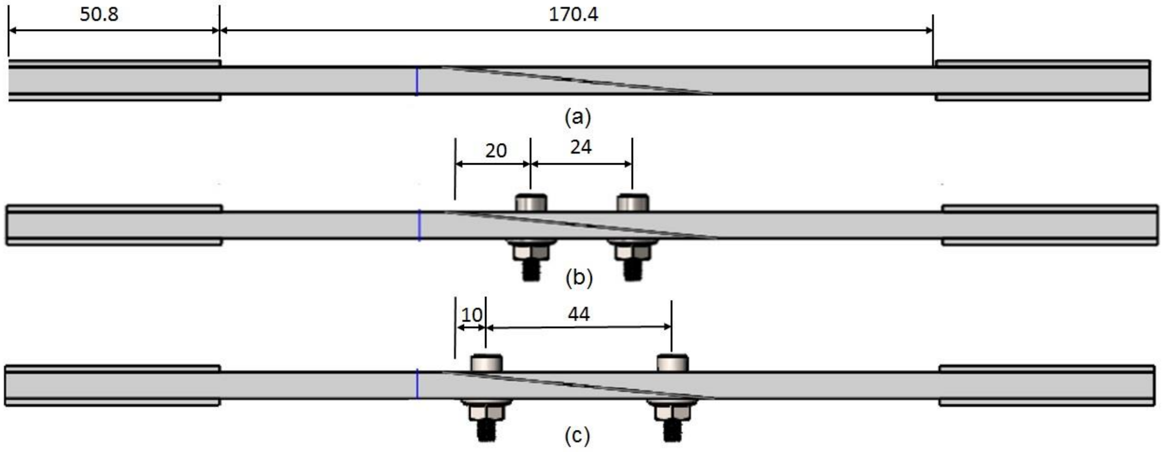

Figure 1: Scarf joint configurations (a) Bonded scarf joint, (b) Scarf joint with fasteners placed at 24 mm each other (Hybrid A), and (c) Scarf joint with fasteners placed at 44 mm each other (Hybrid B) (all dimensions are in mm).

Fasteners used for hybridization of the scarf joints are M4 galvanised socket cap steel bolts with flat and M4 heavy hex nut. Fasteners are also incorporated with washers, to provide partial lateral clamping pressure on the joint [18]. The nut was finger tightened prior to the testing of the specimen. The scarf joint with and without mechanical fasteners are shown in Figure 2.

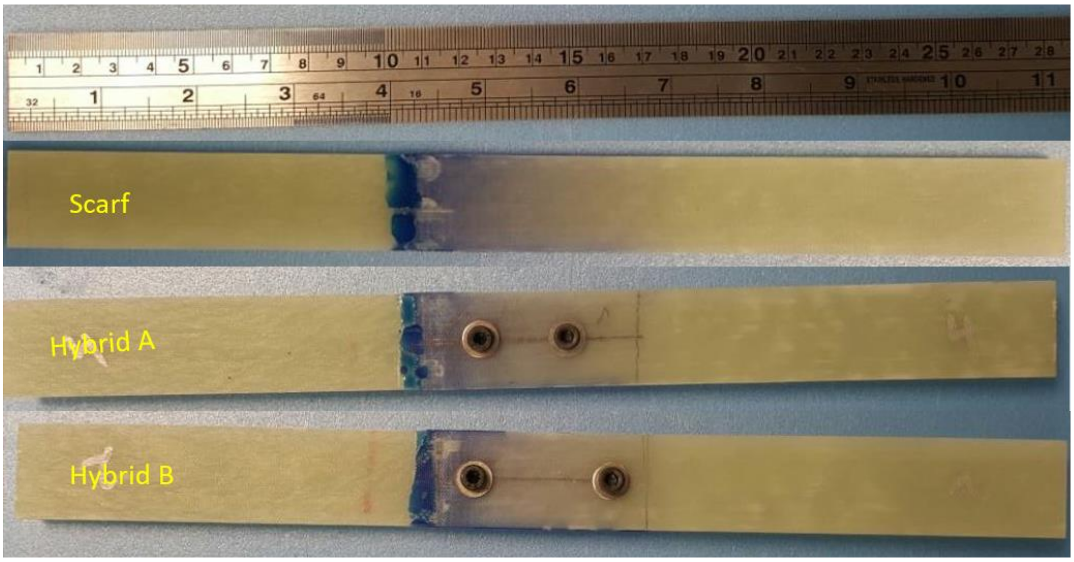

Figure 2: Fabricated Scarf joint with two different fastener positions.

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 50kN load cell. Prior to testing of the scarf specimen 1.5 mm thick, 25.4 mm wide and 50.8 mm long woven (8 harness weave) GFRP end tabs were attached to the test sample as shown in Figure 1 on either side of the scarf joint using cyano-acrylic adhesive to avoid slipping and adherend damage due to gripping pressure. The experimental set up with strain gauge bonded to the adherends are shown in Figure 3.

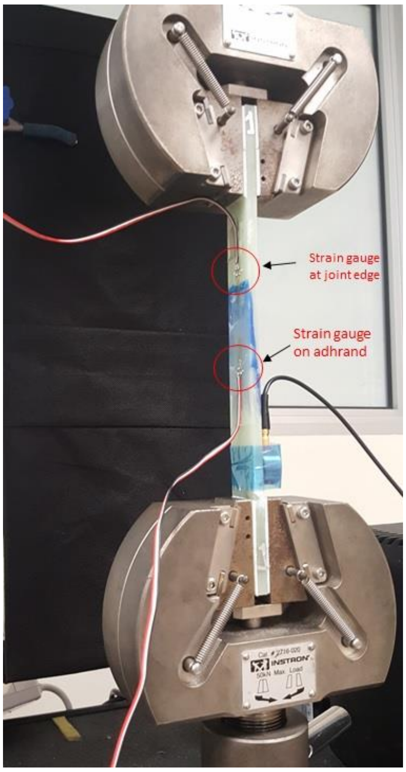

Figure 3: Tensile test set up with strain gauge locations

4 RESULTS AND DISCUSSION

4.1 JOINT STRENGTH AND STIFFNESS

It is expected that the adhesively bonded scarf joint of 5^0 are expected to fail by adhesive cohesive failure of thin adhesive layers. Figure 4 illustrates the average load-displacement curves for the bonded and hybrid joints with different fastener position. From the illustration, it is evident that the adhesive failure is taking place in a very close loading range for all three configurations.

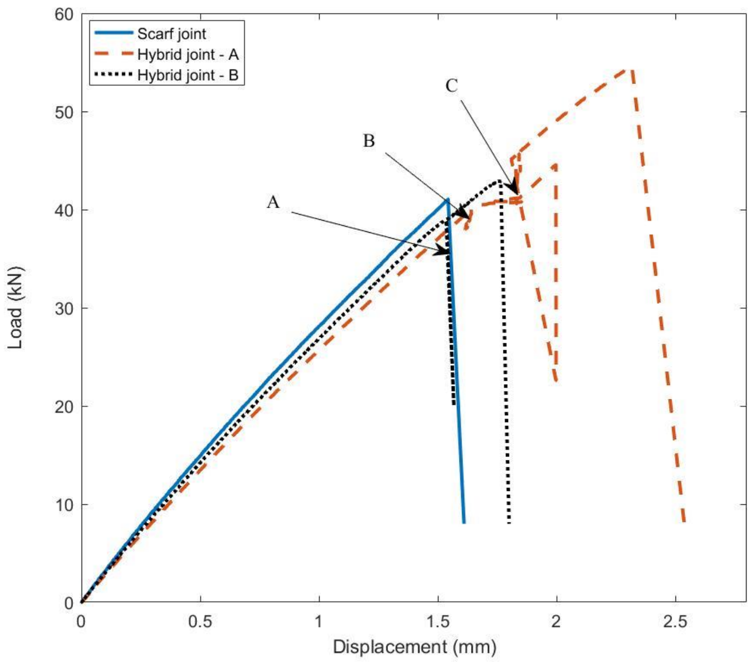

Figure 4: Load-displacement curve for different joint configurations

At higher loading, near the non-linear region of the load-displacement curve, the mechanical fastener starts to bear a higher share of the applied load. This means that the fasteners contribute to the load path once the adhesive loses its load carrying capacity. At any stage where the gross failure of the adhesive occurs, the joint load drops to a level from where the mechanical fastener will start to sustain resulting to the transformation of the adhesive joint to the mechanically fastened joints. From the Figure 4, it can be seen when the mechanical fasteners are placed at 24 mm away from each other they have a distinct point B where partial adhesive failure takes place. This is followed by the load plateau where the remnant adhesive behaves non-linearly up to a point C.

There is an abrupt adhesive failure which can be seen with a sudden load drop until mechanical fasteners start recovering the load drop. This is possibly due to the tolerance between the fastener hole and the bolt diameter. Similarly, when the fasteners are placed at 44 mm away from each other the adhesive layer abruptly fails (point A) until the mechanical fasteners start recovering the load drop. Both hybrid joints exhibit different nature of load bearing and recovery. The close configuration can bear substantially higher loads post adhesive bond failure. On the contrary, the configuration where the fasteners are placed away from each other (Hybrid B) able to bear only a small amount of load post load recovery. Two possible reasons can be given for such behaviour are a) overlapping of stress concentration regions from the fastener hole and joint edge and b) shorter length of shear out region between the fastener and the joint edge.

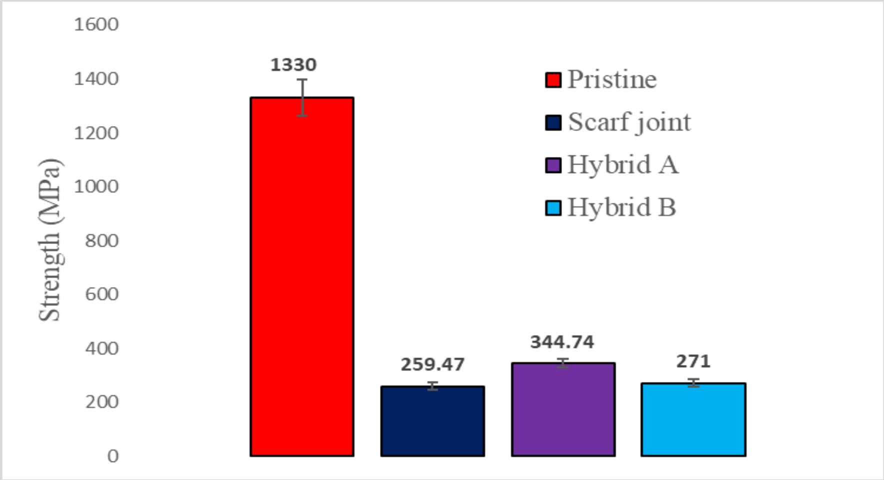

Figure 5: Strength comparison of different joint configuration

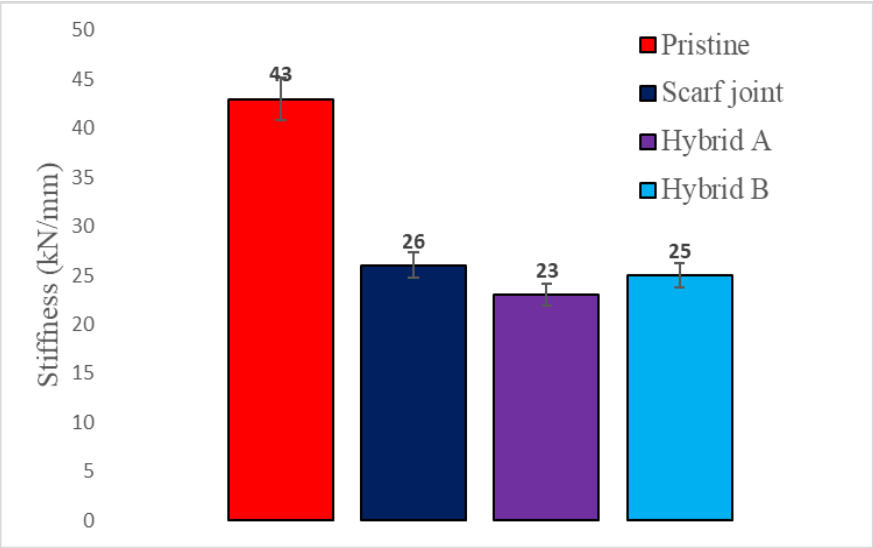

Figure 6: Stiffness comparison of different joint configuration

The strength of different joint configurations is compared with the pristine specimens (G17500 uniaxial testing) as illustrated in Figure 5. The adhesively bonded scarf joints have the poor joint strength (80 % reduction) than the pristine ultimate tensile strength. However, the joint strength could be improved to certain extend by enriching with mechanical fasteners, up to 5% for hybrid B and 32% for hybrid A as shown in Figure 5. The comparison of the stiffness of the joints is shown in Figure 6. There is a deviation of 39% between the pristine and bonded scarf joint. However, there is only a 10% difference in stiffness between the joint configurations are found which ensures that the fasteners have minimal influence on stiffness.

4.2 LOCALIZED JOINT STRAIN

The strain in the vicinity of scarf joint was examined to understand the localised strain effects of hybrid joints. Strain gauges of 350 Ω and coefficient of thermal expansion of 70 x $10^{-6}/^{o}C$ are installed carefully in the centre of the scarf joint and at the joint edge as shown in Figure 3.

The strain elapsed during the tensile testing of bonded scarf joint for all three configurations of bonded joints are compared in Figure 7. Data from strain gauge installed at the edge of adherend overlap illustrates the intensity of fracture-induced than the centre of the adherend. For scarf joint without fasteners the difference in strain is minimal that ensures a smooth load transition between two adherends. The strain increases more rapidly than the hybrid joints initially until higher shear resistance is offered by the adhesives. On the contrary, there is a strain disparity between the edge gauge and the gauge located between the fasteners of the hybrid joints. This is because of the transition of load path from a uniform adhesive interface to the discrete fastener interface. At initial stages of loading, the strain transition of the hybrid joints is shallow due to the frictional effects of the torque applied to the fasteners. In the case of Hybrid B, the strain gauge at the edge fails immediately after the adhesive failure but the gauge between the fasteners continuous to strain. Both hybrid joints have displayed similar strain characteristic when the data from the strain gauge installed on the joint edge is analysed. Although, the hybrid joint with fasteners placed 24 mm away from each other (Hybrid A) have shown greater strain recovery.

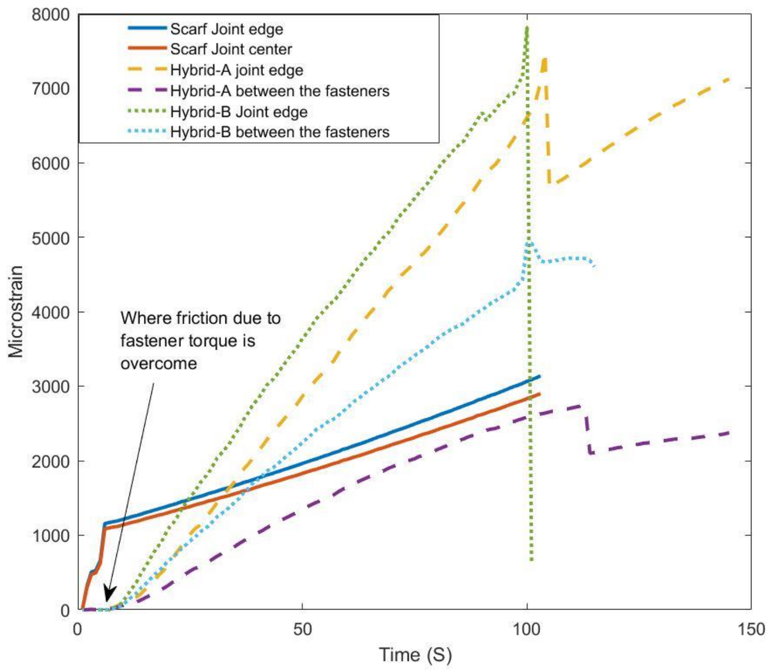

Figure 7: Strain response at joint edge and centre of the scarf joint.

4.3 FAILURE MODES

The fractured bonded surface of all three configurations under study is shown in Figure 8. The failed surfaces near the scarf edges of both adherends exhibit an adhesion failure whereas the centre of the scarf adherend exhibits a partial cohesive failure as shown in Figure 8(a). The traces of adhesives found in the thickest regions of the scarf. There is also adherend cracking found in the edges of the scarf due to unidirectional nature of the laminate. Figure 8(a) and (b) represent fractured surfaces of the hybrid joints of two configurations, fractured surface of hybrid A that is fastener spaced 24 mm apart have incurred predominant partial adherend shear tear out. Hybrid B has incurred complete shear tear out that starts from inward fasteners to the edge of the scarf.

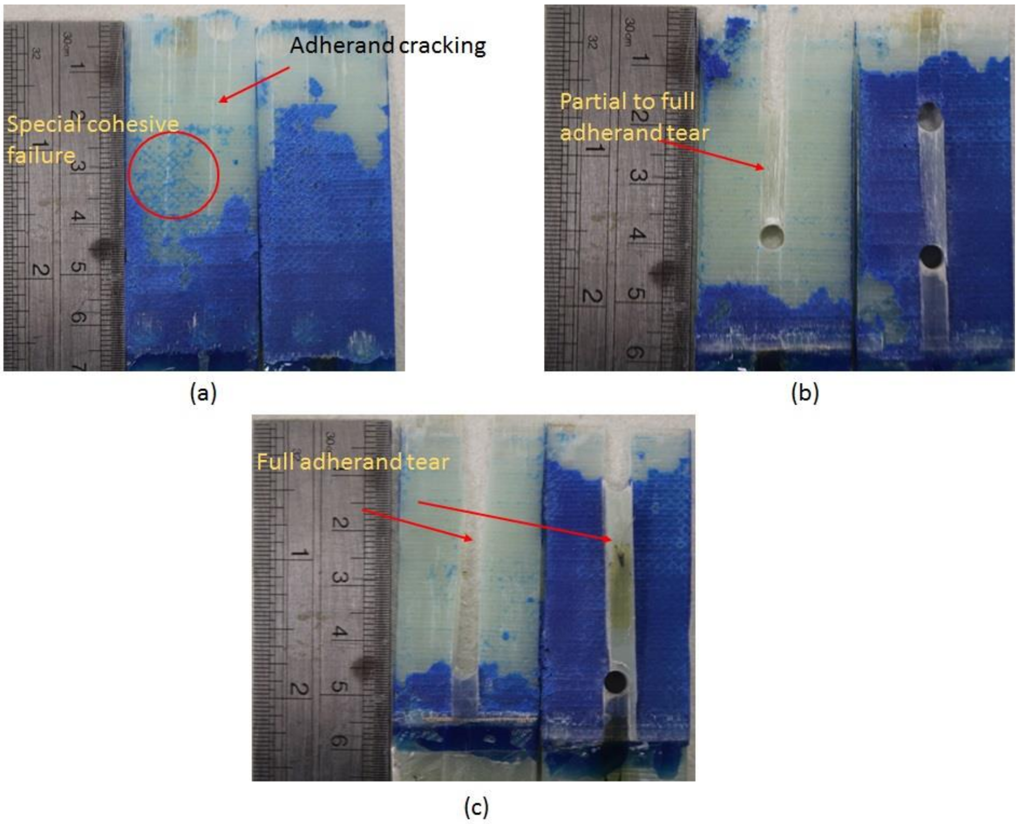

Figure 8: Fractured bond-line surface of (a) adhesively bonded scarf joint, (b) hybrid scarf joint with fasteners placed 24 mm apart (Hybrid A), and (c) hybrid scarf joint with fasteners placed 44 mm (Hybrid B) apart

9 CONCLUSIONS

The load carrying capacity of the hybrid joints enriched with mechanical fasteners was investigated for two different fastener locations. The location of the fastener from the scarf edge influence the joint edge strain and failure mode of the adherends. Further, bolts do not take an active role in load transfer before the initiation of adhesive failure. There is a time lag in load transfer during the transition from adhesive failure to fastener load pick up. The ultimate load carrying capacity of the joints is improved with the enrichment of fasteners. However, there is a marginal difference in stiffness among different joint configurations observed. The strain gauge measurement reveals that there is a strain concentration at the edges of the joint. Especially, the strain at the edges of hybrid B is predominant than other configuration owing to the small edge distance of the fastener hole. This leads to a complete tear out of the unidirectional adherends.

ACKNOWLEDGEMENTS

The authors thank Mr. Yew Ying Yeow for his help with the sample machining work. I. Sridhar thanks MAE for the research incentive grant on the design with hybrid composite materials work.

REFERENCES

1. Gunnion, A.J. and I. Herszberg, *Parametric study of scarf joints in composite structures.* Composite structures, 2006. **75**(1): p. 364-376.
2. Moreira, R. and R. Campilho, *Parametric Study of the Reinforcement Geometry on Tensile Loaded Scarf Adhesive Repairs.* The Journal of Adhesion, 2016. **92**(7-9): p. 586-609.
3. Gleich, D.M., M.J.L. Van Tooren, and P.A.J. De Haan, *Shear and peel stress analysis of an adhesively bonded scarf joint.* Journal of Adhesion Science and Technology, 2000. **14**(6): p. 879-893.

4. Baker, A., et al., *Scarf repairs to highly strained graphite/epoxy structure.* International Journal of Adhesion and Adhesives, 1999. **19**(2-3): p. 161-171.
5. Pipes, R., D. Adkins, and J. Deaton, *Strength and repair of bonded scarf joints for repair of composite materials.* NASA Langley Research Center, MSG, 1982. **1304**.
6. Kwon, Y. and A. Marron, *Scarf joints of composite materials: testing and analysis.* Applied Composite Materials, 2009. **16**(6): p. 365.
7. Kumar, S., et al., *Tensile failure of adhesively bonded CFRP composite scarf joints.* Materials Science and Engineering: B, 2006. **132**(1): p. 113-120.
8. Adin, H., *The effect of angle on the strain of scarf lap joints subjected to tensile loads.* Applied Mathematical Modelling, 2012. **36**(7): p. 2858-2867.
9. Pinto, A., et al., *Numerical evaluation of three-dimensional scarf repairs in carbon-epoxy structures.* International Journal of Adhesion and Adhesives, 2010. **30**(5): p. 329-337.
10. Campilho, R.D.S.G., et al., *Modelling the tensile fracture behaviour of CFRP scarf repairs.* Composites Part B: Engineering, 2009. **40**(2): p. 149-157.
11. Xiaoquan, C., et al., *Study of tensile failure mechanisms in scarf repaired CFRP laminates.* International Journal of Adhesion and Adhesives, 2013. **41**: p. 177-185.
12. Hart-Smith, L., *Design Methodology for Bonded-Bolted Composite Joints. Volume I. Analysis Derivations and Illustrative Solutions*. 1982, DTIC Document.
13. Bodjona, K. and L. Lessard, *Hybrid bonded-fastened joints and their application in composite structures: A general review.* Journal of Reinforced Plastics and Composites, 2016. **35**(9): p. 764-781.
14. Chowdhury, N.M., et al., *Static and fatigue testing bolted, bonded and hybrid step lap joints of thick carbon fibre/epoxy laminates used on aircraft structures.* Composite Structures, 2016. **142**: p. 96-106.
15. Kelly, G., *Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints.* Composite structures, 2006. **72**(1): p. 119-129.
16. Kelly, G., *Load transfer in hybrid (bonded/bolted) composite single-lap joints.* Composite structures, 2005. **69**(1): p. 35-43.
17. Bois, C., et al., *An analytical model for the strength prediction of hybrid (bolted/bonded) composite joints.* Composite Structures, 2013. **97**: p. 252-260.
18. Hoang-Ngoc, C.-T. and E. Paroissien, *Simulation of single-lap bonded and hybrid (bolted/bonded) joints with flexible adhesive.* International Journal of Adhesion and Adhesives, 2010. **30**(3): p. 117-129.