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Fatigue Loading of Polymer Composite Lap Joints with Washers Inserted in the Lay-up

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Abstract. Carbon fibre-reinforced composites are still more often incorporated into aircraft structures, primary structures included. This also increases the need to join individual elements of the aircraft construction into complex components. Single lap adhesive bonded joints with one fastener were evaluated. A new approach of reinforcing the bolted hole using an inserted aluminium washer in the composite lay-up was used. Two types of washers were used – smooth washer and 3D printed spiked washer. A cross-section analysis showed some minor resin rich areas and voids on the washer contact with the composite. Fatigue crack fronts in the adhesive during loading were marked based on single transducer ultrasonic probe. The C-scan revealed also crack initiation from the washer border. The washer reinforced series had lesser final crack acceleration and thus showed improved fatigue behaviour in comparison with the reference specimen. Spiked 3D print washer improved the fatigue life by 28 %. The failure mechanism was also explained. Bonded joints currently do not meet airworthiness requirements and it is the motivation for the innovative research of the composite joints.

Introduction

Carbon fibre-reinforced polymer (CFRP) laminates are used in aerospace due to their effective strength to weight ratio. The major classification of composite joints in aircraft structures are the bonded and bolted joints. Regarding the bolted joints, drilling holes for fasteners cause fibres interruption and thereby weakens the construction. In addition, holes can act as stress concentrators and composite bearing strength is also quite low which is connected with the compression strength that is lower than in tension. On the other hand, bonded joints has lower weight and very good sealing to the structure. They also distribute the load uniformly over the bonded area [1, 2]. However, bonded joints are not effective in transferring high loads because the composite material itself has lower resistant to interlaminar shear stresses and also bonded joints are very sensitive to environmental conditions.

Composite aircraft structures are currently primarily bonded by riveting or bolting. Adhesive bonding of thin-walled composite structures is a very promising method that could replace the fasteners. Adhesively secondary bonding would considerably contribute to the weight and cost reduction. Therefore, it is the motivation for the current research of the bonding joints. For secondary structures, adhesive bonding is a common practice but until today the certification rules that are applicable for primary bonded structures prevent the use of bolt-free bonded joints for primary structures, as a result of earlier experiences, where the interpretation of the rules led to in-service premature failure incidents on adhesively bonded joints [3]. This is because no non-destructive method can evaluate quality of the joint in terms of strength.

Using fasteners as crack stopping features is one way to achieve the certification [4, 5]. This work investigates possible innovations for the bolted connection using inserted washers to reinforce the bolted area. Other ways of the reinforcement can be titanium-lamella reinforced CFRP bolted joints [6] or metallic inserts with variable thickness used for multiple bolt configuration [7]. These authors stated that the reinforced samples improved the both the strength and total displacement at final failure. Titanium insert hole repairs were also investigated in Ref. [8]. The inserts improved the bearing and pull-through strength and the primary failure did not involve the insert.

This article deals with fatigue life enhancement of composite joints using reinforced holes by metal washers inserted into the lay-up.

Materials and Methods

Single lap adhesive bonded joints with one fastener were used. Two adherents of 20 and 13 plies were joint for each specimen. Length of each adherent was 205 mm, thickness of the non-reinforced 20 ply adherent was 5.7 mm with the lay-up of [(-45/+45)/(+45/-45)/(90/0)/(+45/-45)/(-45/+45)/(0/90)/(-45/+45)/(90/0)/(+45/-45)/(0/90)]s and thickness of the washer reinforced 13 ply adherent was 3.7 mm with the lay-up of [(+45/-45)/(-45/+45) /(0/90)/(90/0)/(+45/-45)/(-45/+45)/(0/90)/(-45/+45)/(+45/-45)/**(90/0)/(0/90)/**(-45/+45)/(+45/-45)**]**s. The washer was inserted in the two (90/0) cut-out layers highlighted by the bold text. Overlap length was 60 mm, and width of the specimen was 35 mm. The joints were bonded by film adhesive (REDUX FM300) and fastened by a fastener (ABS1707 B C2 V1 A – 5 mm in diameter).

The reference sample and two types of innovative technologies for joining of CFRP laminates were evaluated. Two types of washers inserted into the carbon fibre fabric laminate during manufacturing were used for the innovative specimens - smooth washer and spiked 3D print washer. The washers were made of aluminium alloy. Surface of the smooth washer was free from any protrusion, roughness or any other inequalities (Fig. 1). The thickness was not constant with lower thickness far from the hole. The cross-section in Fig. 1 showed significant resin rich areas on both surfaces of the smooth washer and also a significant resin pocket on the washer border. Spiked 3D print washer had on the surface hooks, which should ensure better cohesion with laminate (Fig. 2). Unlike the smooth washer, the contact area with the composite was without resin rich areas. However, there were some voids around certain hooks.

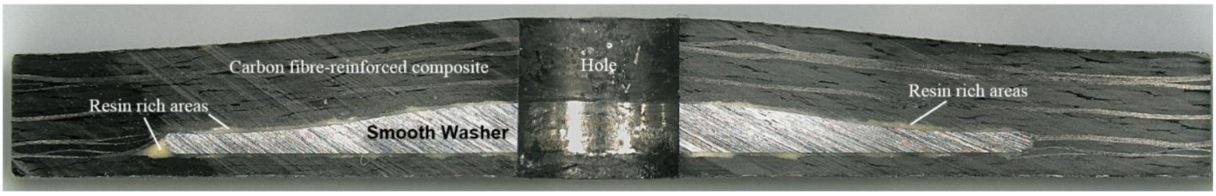


Fig.1 Cross-section of a composite adherent with inserted aluminium smooth washer

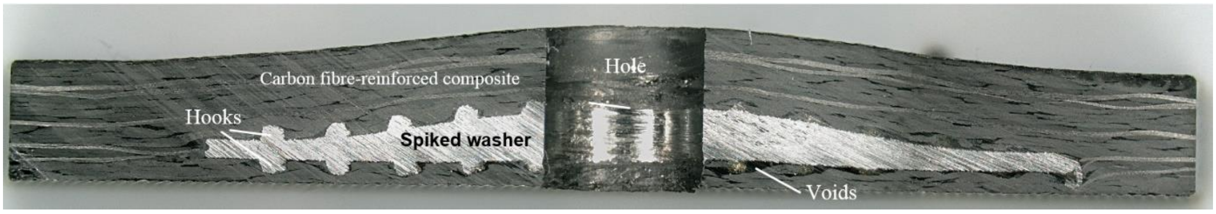


Fig.2 Cross-section of a composite adherent with inserted aluminum 3D spiked washer

Loading machine Instron 55R1185 with 100 kN load cell was used for quasi-static testing. Crosshead displacement rate was set to 1 mm/min. The extensometers were used for displacement measurement of static tests.

The fatigue tests were performed on INOVA ZUZ 100 kN and Hydropuls Schenck 250 kN with maximum load of 8 600 N and coefficient of asymmetry $R = 0.1$. In selected intervals C-scan using a phased array probe was performed (Olympus – Omniscan). The crack front was monitored using a single probe A-scan in regular intervals.

Results

The static testing load-displacement curves are shown in Fig. 3. There is significant load drop after the peak at approx. 25 kN where the adhesive failed. This load drop was not depended on the reinforcement as the adhesive was the same for all the series. After the drop to, the load was carried only by the fastener. Spiked washer reinforced series had higher bearing load (10 kN) than reference series by approximately 35%. This was caused by the higher cross-section surface as the thickness around the reinforcement was increased by the washer.

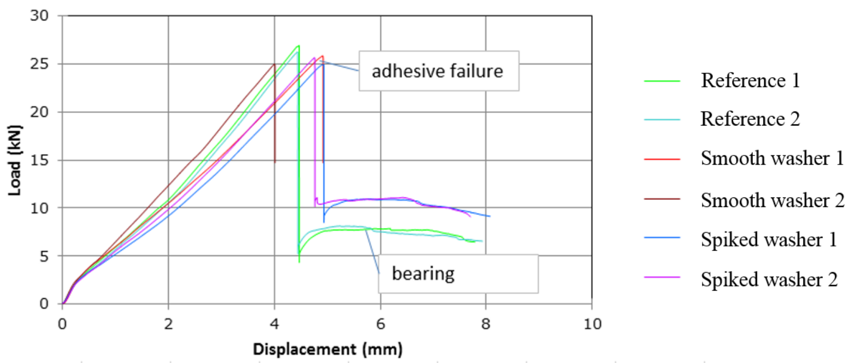
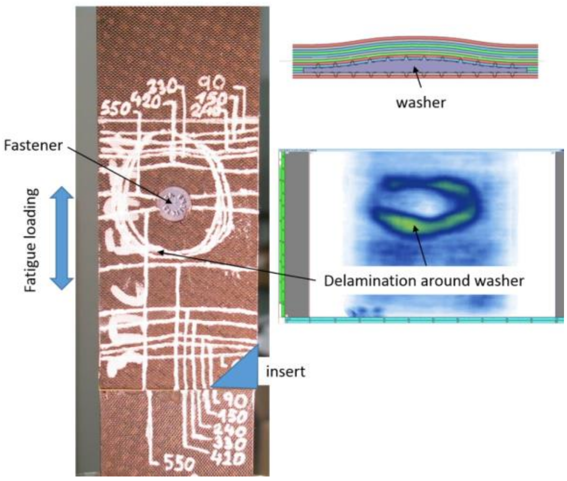


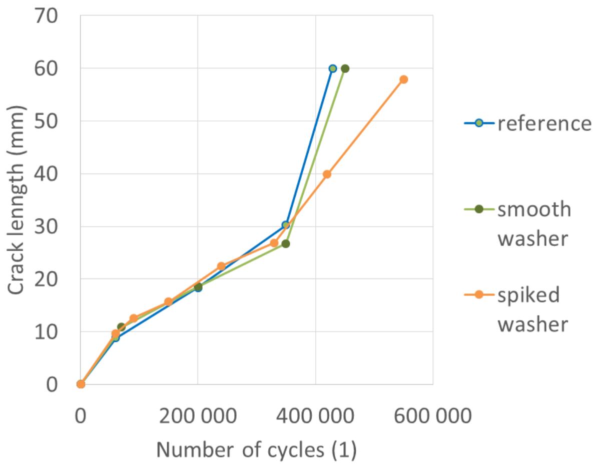
Fig.3 Results of quasi-static testing of a single lap joint with adhesive bonding and a fastener

The results of fatigue crack growth of a single lap joint with adhesive bonding and a fastener are shown in Fig. 4. Fatigue crack fronts during loading were marked based on single transducer ultrasonic probe. Typically the crack propagated first from the bottom edge and then from the upper. Near the lower edge corner, there was an insert to initiate the crack. However, there was no proof that this insert really initiated the crack because the crack front was typically straight and the insert seemed to be also bonded to the laminate. The C-scan revealed also crack initiation from the washer border. This could be caused by the two layers that were cut-out before inserting the washer. The border around the washer than behaved as a stress concentrator.

The crack growth rate was evaluated based on the delaminated area that was divided by the specimen width. The delamination curves are shown in Fig. 4 where both lower and upper cracks are included. There is higher crack growth rate for the lower edge in the beginning that could be caused either by the insert or by the higher peel forces in the area more far from the fastener. Then, there was stable crack growth until 350 000 cycles where the both lower and upper crack accelerated. The washer reinforced series had lesser final crack acceleration and thus showed improved fatigue behaviour in comparison with the reference specimen. There was 5 % fatigue life improvement for smooth washer specimens and 28 % fatigue life improvement for spiked 3D print washer joints when compared to reference specimens.



a) Fatigue crack fronts during loading and a delamination initiation from the washer.



b) Fatigue crack growth curves for the reference and two reinforced joints.

Fig.4 Results of fatigue crack growth of a single lap joint with adhesive bonding and a fastener

A macro photography of fracture surfaces revealed fibre and adhesive dominated fracture which corresponded with crack growth and shearing direction. The mechanism of angled cracks is explained in Fig. 5. The cracks initiated at both free edges and then they were driven diagonally toward one of the bonded surface due to the shear forces that caused 45° major stress direction. The cracks propagated along the interfaces until they reached the bolt. The crack propagation in both planes caused the splitting of the fibre dominated (black) and adhesive dominated (green) fracture surface.

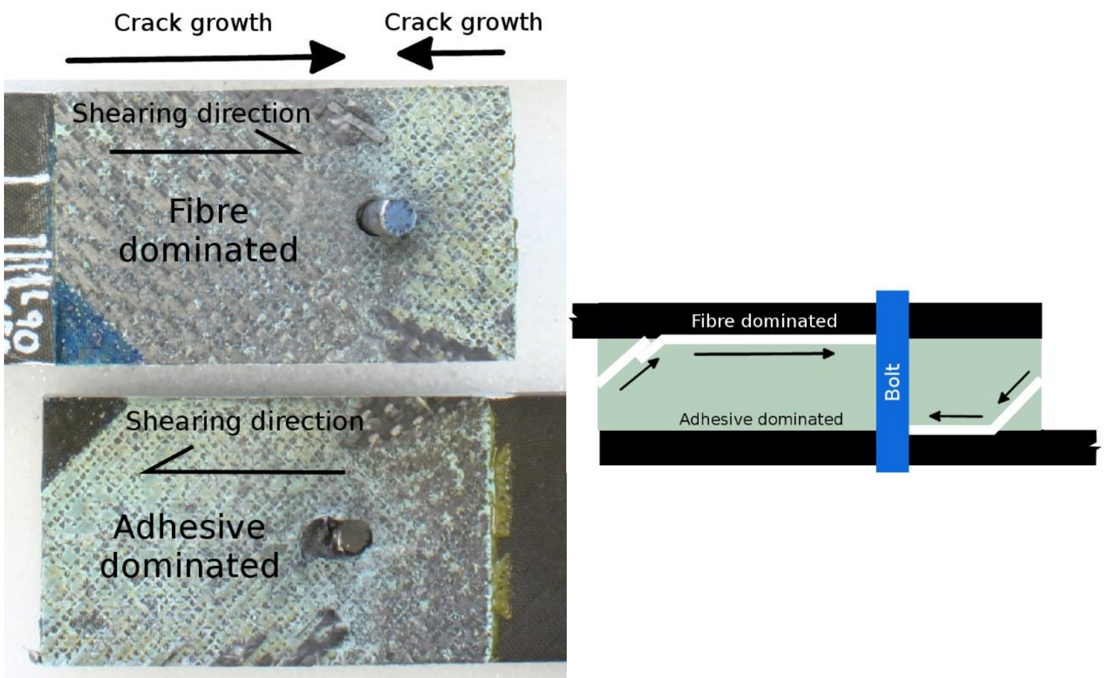


Fig 5 Fatigue crack fracture surface with explained angled crack mechanism leading to fibre and matrix dominated fracture

Conclusion

To conclude, the results of fatigue loading of single lap shear joints showed that the reinforcement influenced only the final stage of crack growth where it hindered the crack and increased the joint lifetime by 30%. The fatigue crack growth mechanism leading to fibre and matrix dominated fracture surface was also explained. The crack stopping features have great potential to certificate adhesive joints for primary aerospace structures.

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References

[1] Sp. Pantelakis, K.I. Tserpes, Boltless joining of composite aerostructures: From secondary to primary parts: International Conf. On Airworthiness & Fatigue – 7th ICSAELS Series Conf. 25-27 March, 2013 Beijing, China.

[2] R. Jones, A.J. Kinloch, W. Hu, Cyclic-fatigue crack growth in composite and adhesively-bonded structures: The FAA slow crack growth approach to certification and the problem of similitude, International Journal of Fatigue 88 (2016) 10-18, http://dx.doi.org/10.1016/j.ijfatigue.2016.03.008.

[3] Banea MD, da Silva LFM. Adhesively bonded joints in composite materials: an overview. *Proc. IMechE Part L: J. Materials: Design and Applications, 2009*; **223**: 1-18.

[4] K.I. Tserpes, G. Peikert, I.S. Floros, Crack stopping in composite adhesively bonded joints through corrugation, Theoretical and Applied Fracture Mechanics 83 (2016) 152-157, http://dx.doi.org/10.1016/j.tafmec.2015.10.003.

[5] T. Kruse, T. Körwien, R. Růžek, Fatigue behaviour and damage tolerance design of composite bonded joints for aerospace application, ECCM 2016 - Proceeding of the 17th European Conference on Composite Materials2016; Code 126913, ISBN**:** 978-300053387-7

[6] G. Kolks, K.I. Tserpes, Efficient progressive damage modeling of hybrid composite/titanium bolted joints, Composites Part A: Applied Science and Manufacturing 56 (2014) 51-63, http://dx.doi.org/10.1016/j.compositesa.2013.09.011.

[7] V. Kradinov, E. Madenci, D.R. Ambur, Bolted lap joints of laminates with varying thickness and metallic inserts, Compos Struct 68 (2005) 75–85. doi:10.1016/J.COMPSTRUCT.2004.03.00.

[8] D. Falconieri, F. Franco, The effect of titanium insert repairs on the static strength of CFRP coupons and joints, Composite Structures 134 (2015), 799-810.