IMPROVING THE DAMAGE TOLERANCE OF COMPOSITE JOINTS WITH TUFTING

James Kratz[1], Harry Clegg[2], Giuseppe Dell'Anno[2] and Ivana K Partridge[1]

[1] Advanced Composites Centre for Science and Innovation, University of Bristol
Queen's Building, University Walk, Bristol, United Kingdom BS8 1TR
Email: james.kratz@bristol.ac.uk and ivana.partridge@bristol.ac.uk,
Web page: http://www.bristol.ac.uk/composites/

[2] The National Composites Centre
Feynman Way Central, Bristol & Bath Science Park, Emersons Green, United Kingdom BS16 7FS
Email: harry.clegg@nccuk.com and giuseppe.dellanno@nccuk.com,
Web page: www.nccuk.com

Keywords: 3D reinforcement, Damage tolerant joints, Automated manufacturing, Tufting

ABSTRACT

Glass fibre T-stiffened skin-stringer joints were manufactured with through-thickness carbon fibre reinforcement using a one-sided stitching technique, known as tufting. Specimens were tested in four-point bending to identify the delamination trigger mechanisms and mitigate damage within the joint. An untufted control specimen showed that delamination initiates at two transitions within the joint: where the stringer flange meets the skin and where the flange transitions into the web. Continued loading of the untufted joint results in stringer separation from the skin. Tufting successfully increased the initiation failure load by 8 % when tufts were inserted into the flange to skin transition, and by 16 % with additional tufting in the skin at the stringer tip. Delamination between the skin and flange occurred outside the tufted region, but separation of these elements was mitigated, increasing the stiffness and damage tolerance of the joint. Unfortunately, the failure mode changed from skin-stringer peeling to web-splitting. Additional tufts may be required in the flange to web transition to further improve the onset of joint delamination.

1 INTRODUCTION

Delamination remains a frequent failure mode in composite structures and improving their damage tolerance is desirable for both performance and affordability. Composites typically crack in the interlaminar region and increasing the delamination resistance involves reducing crack initiation and/or crack propagation [1]. Several techniques are currently available to enhance the delamination resistance of polymer matrix composites, some involve the addition of thermoplastic modifiers to the base thermosetting matrix [2], inclusion of thermoplastic particle interleaved regions [3], while others incorporate 3D fibre architectures [4].

Crack initiation and propagation is a particular concern in joints, where out-of-plane loading increases the likelihood of delamination failure between elements. Adding a discrete amount of through-thickness reinforcement to physically link adjacent fibre layers subjected directly to out-of-plane loads has been identified as a potential solution to overcome delamination propagation in structures made by both prepreg and liquid composite moulding routes [5]. Stitching has been shown to have a detrimental effect on the in-plane properties of composites structures [4]. The tensile and compressive moduli are reduced because the highly aligned in-plane fibre network is disturbed by the penetrating needle and the final crimp. Fortunately, there is rarely a need to reinforce the whole structure. Using a local through-thickness reinforcement approach allows designers to add reinforcement discretely to areas most susceptible to delamination, while minimising the knockdown of in-plane properties.

One practical limitation of most stitching technologies is the need to simultaneously access both the top and bottom sides of the preform to interlock the stitching thread. One-sided stitching techniques are available to reduce the manufacturing complexity. Tufting is such a single-sided process, whereby a single needle inserts a single dry thread into the reinforcement without tension. A disposable backing material is required on the other side of the preform to form the loops and prevent the thread from moving during needle retraction [6]. The tufted preform can be infused using traditional resin infusion methods, and the tufts (Figure 1) have been successful at arresting cracks and even recovering the load path in T-stiffened structures tested in pull-out [5].

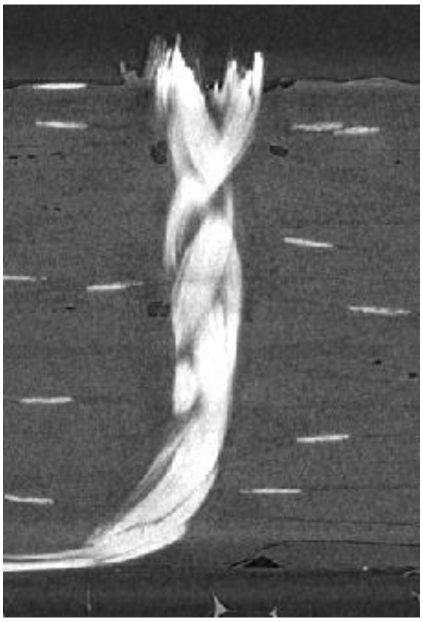


Figure 1: Micro-CT image of a glass tuft in a carbon fibre laminate (from [7]).

Stiffening elements are commonly used in composite structures, and they often fail by delamination where the stringer tip terminates [8–11]. The transition region between the skin and stringer in skin-stiffened panels presents a unique opportunity to locally increase the interlaminar fracture toughness in a region where high out-of-plane loads would otherwise cause delamination, without lowering the global in-plane stiffness that would arise if the complete structure were reinforced. In this paper, the flange transition of a T-stiffened skin-stringer was reinforced through-thickness with tufting to investigate the effect of local reinforcement on delamination initiation and subsequent crack propagation.

3 EXPERIMENTAL

Specimens were tufted in two configurations to identify what trigger mechanisms cause crack initiation and subsequent propagation through a skin-stringer transition. A control specimen with no tufts was also manufactured and tested for comparison. Figure 2 shows the location and number of tufts in the stiffened panels. The skin was 8 mm thick and the flange 4 mm thick, with a stacking sequence of $[-45/45/90/45/-45/0]_{4S}$ and $[-45/45/90/45/-45/0]_{2S}$, respectively. The total thickness of the web was 8 mm. The transition between the skin and flange of the T-stiffener was manufactured by dropping plies every 2 mm, resulting in a 8.5° ramp, with a 1 mm step in the preform. This step was included to have one covering ply for every 4 dropped plies. The infusion tooling was manufactured without a step to ensure a smooth transition between the skin and flange, but a local resin rich region is expected.

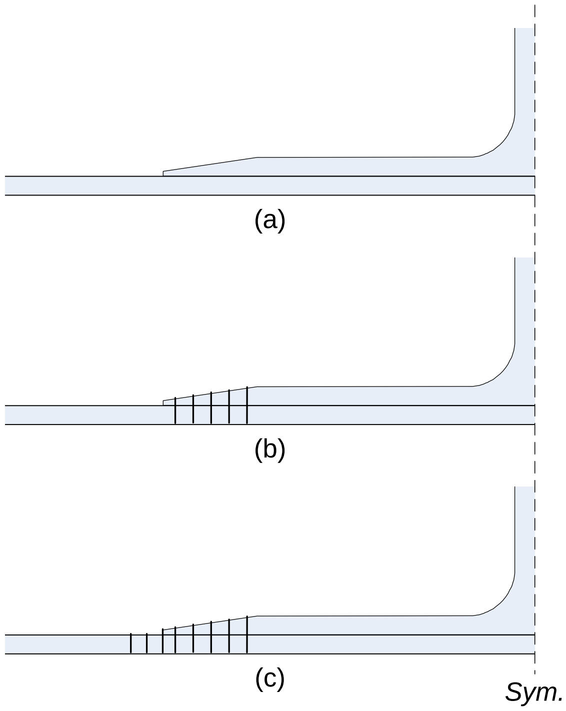


Figure 2: Specimen tufting configurations (a) untufted, (b) stringer transition, and (c) stringer transition and adjacent skin.

3.1 Materials

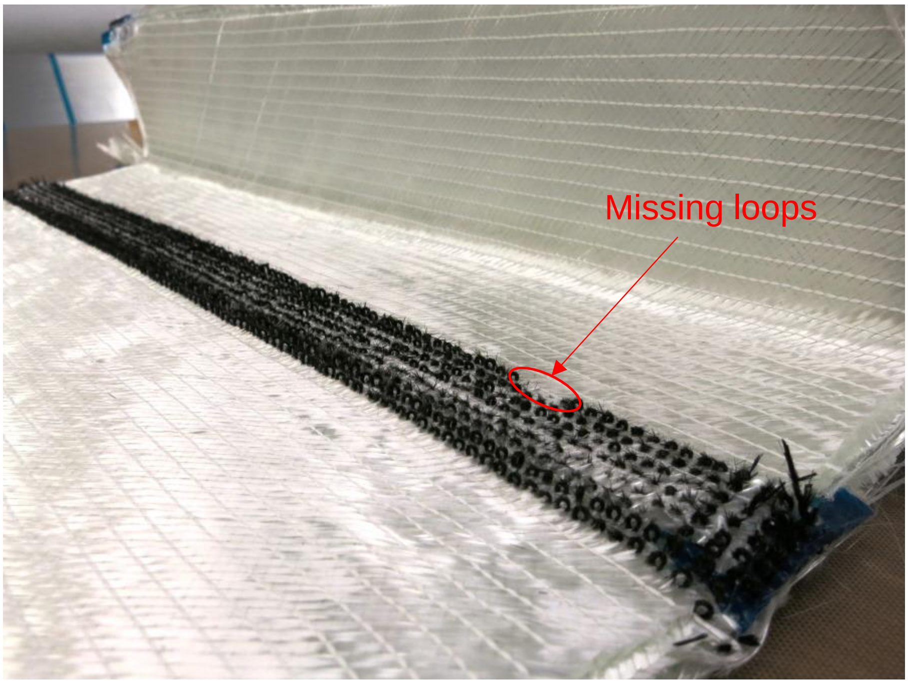
The skin-stringer composite structure was manufactured with a standard E-glass fibre bi-axial (±45°) non-crimp fabric (NCF) with an areal weight of 440 g/m^2. A commercial grade, industrially proven 4 × 1K HTA 40 carbon fibre reinforcement thread from Toho Tenax was inserted into the preform at a 3.5 mm spacing using the patterns described in Figure 2. The preform was vacuum infused with Epikote 935 bisphenol A/F resin and Epokure 936 amine hardener from Momentive Speciality Chemicals. The resulting cured ply thickness was 0.34 mm, yielding a fibre volume fraction of 49.3 % for a void free laminate.

3.2 Test Specimen Manufacturing

The skin-stinger run-out panels were tufted, using a KSL RS522 tufting head, shown in Figure 3, mounted to a Kuka robot, located at the National Composites Centre. The preform was held securely during tufting using an aluminium extrusion framed fixture clamped to a table. A foam backing was machined with the profile of the skin-stringer from Airex R63.80 foam. This specific foam was previously identified as suitably rigid for supporting a preform during tufting and suitable compliant to allow the tufting needle to penetrate [6]. This foam was covered in a single layer of low temperature vacuum bagging film, to aid in the retention of the tufts when the preform was removed from the foam backing.

Figure 3: Tufting glass skin-stringer panel with carbon thread

Figure 4 shows the preform once the foam backing was removed, just prior to vacuum infusion. A few (3–4) loops were missing towards one end of the tufting seam (Figure 4a), and some variation in loop size was observed (Figure 4b), but overall full loops were formed during the tufting process. The bend radius of the loops caused some filament fragmentation in the thread (Figure 4b), and this cannot be avoided without moving to alternative tufting threads, such as stretch-broken or aramid [6].



(a)

(b)
Figure 4: (a) carbon tufts in transition of the preform before infusion and (b) filament fragmentation in the loops.

3.3 Test Method

The skin-stringer joints were tested in four-point bending using a hydraulic testing machine with a 25 kN load cell. A schematic of the test set-up is shown in Figure 5. The upper span was 94 mm, the lower span was 250 mm, and the specimen was 30 mm wide. Ideally, the upper span would be 200 mm to introduce a constant moment across the stringer. The current test configuration has a linearly increasing moment from the lower rollers to the upper rollers, and as a result, the moment introduced at the stringer tip is lower than the moment at the flange to web transition.

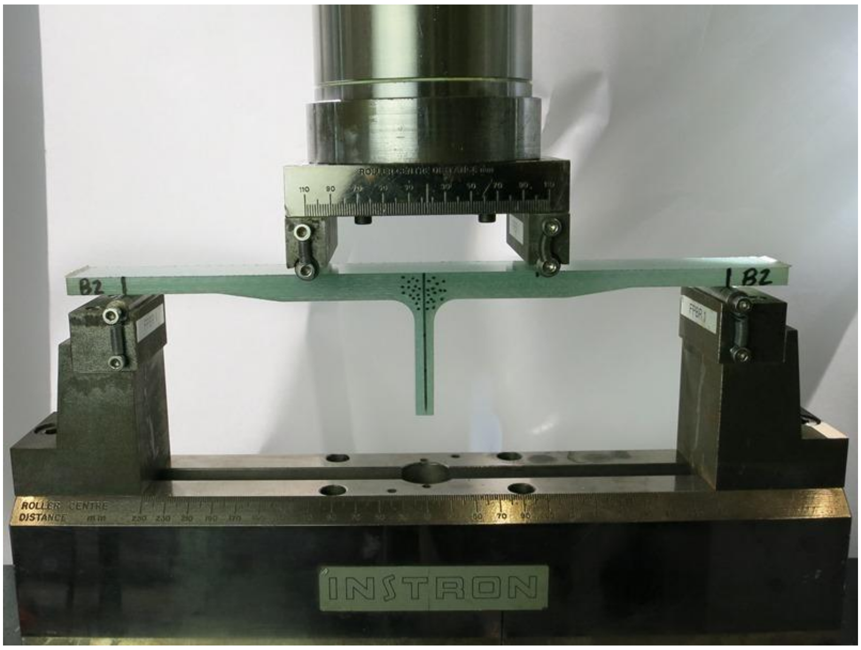


Figure 5: Testing specimens in four-point bending

4 RESULTS

Three specimens were tested for each tufting configuration. One specimen was tested until the joint was about to contact the baseplate of the flexural test fixture, meanwhile, the other two were tested to the first load drop to identify the crack initiation mechanisms. The results of the full-stroke bending test are shown in Figure 6. The untufted control specimen showed the lowest peak load before the onset of delamination. Tufting the stringer transition increased the stiffness of the skin-stringer joint, the onset delamination load, and the sustained damage load. Additional tufts inserted in the adjacent skin to the stringer tip had a similar improvement on performance compared to only tufting the stringer transition. Inserting the tufts clearly improved the damage tolerance as seen by the higher load levels required to propagate damage in the joint.

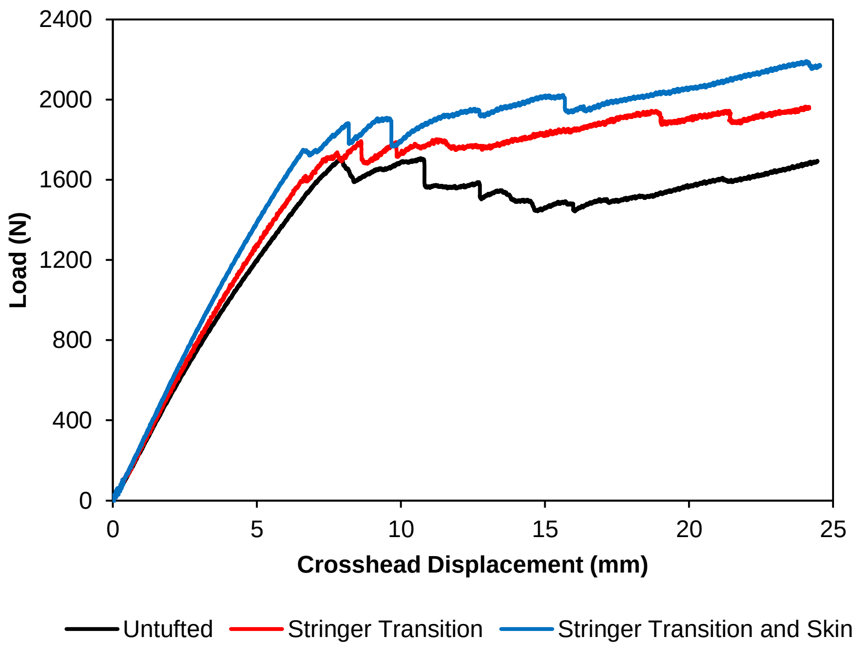
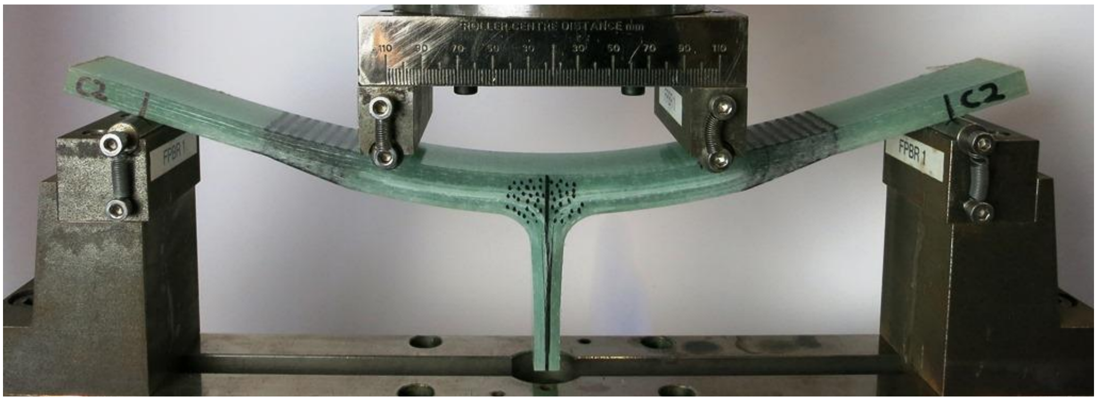


Figure 6: Typical load-displacement plot for the tufted skin-stringer bending tests.

Photographs of the skin-stringer specimens at the end of full-stroke testing are shown in Figure 7. The untufted control specimen shows separation of the stringer from the skin. Once the peak load was reached, the stringer flange delaminated from the stringer tip, peeling towards the web as the crosshead continued to travel. The web remained intact as the damage is located between the stringer flange and skin of the joint. Delamination was again observed in the tufted specimens, but the failure mode was altered. Inserting tufts into the stringer transition prevented the flange from separating from the skin, but delamination was observed between the skin and stringer as a white crack in Figure 7b-c. Since the tufts retained contact between the skin and the stringer flange after delamination, the joint remained in contact and able to sustain load, as measured in Figure 6. Both tufted configurations change the failure mode from stringer tip separation from the skin to web splitting in the stringer. While tufting does increase the damage tolerance of the structure, identifying the trigger mechanisms that initiate delamination, and successful mitigation of these, was of greater interest.

(a) Control

(b) Stringer transition tufted



(c) Stringer transition and skin tufted

Figure 7: Final failure modes observed in the skin stringer panels: (a) delamination originating from the stringer tip in the control specimen, (b) web-splitting and delamination in stringer flange, and (c) reduced web-splitting but delamination in stringer flange.

The results of the bending tests that were stopped after first load drop are shown in Figure 8. Akin to the curves observed in Figure 6, increased tufting correlated to an increased joint stiffness and higher failure initiation loads. Averaging the peak loads of these curves shows that tufting the flange to skin transition (Figure 2b) resulted in an 8 % increase in peak load, further increasing to 16 % when tufting the stringer flange transition and adjacent skin to the stringer tip (Figure 2c). The performance increase from tufting is encouraging, but could be improved. Photographs of an untufted and tufted joint are shown in Figure 9. They reveal that inserting the tufts in the stringer to skin transition was successful at mitigating delamination at the stringer tip, but had no influence on the delamination that initiated in the flange to web transition of the stringer.

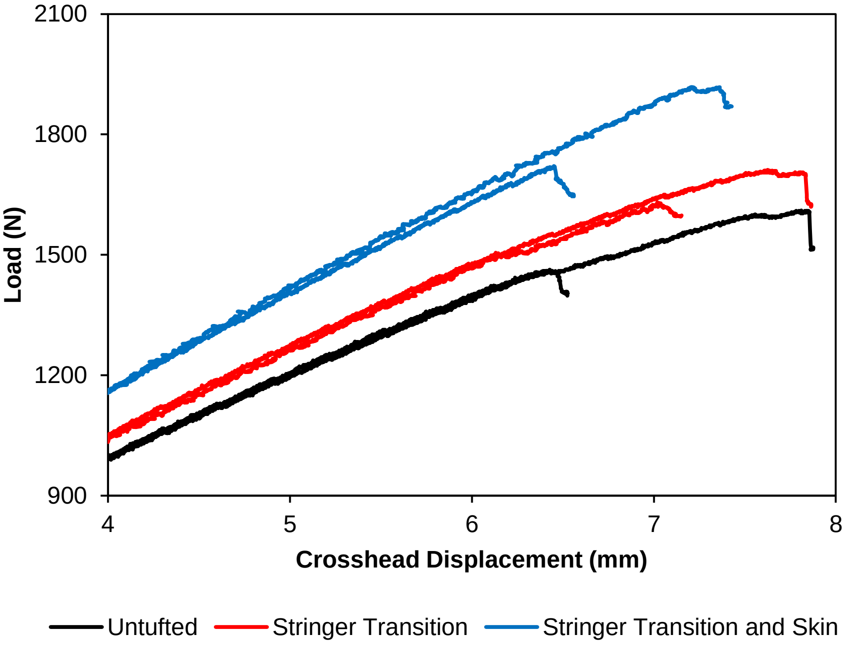
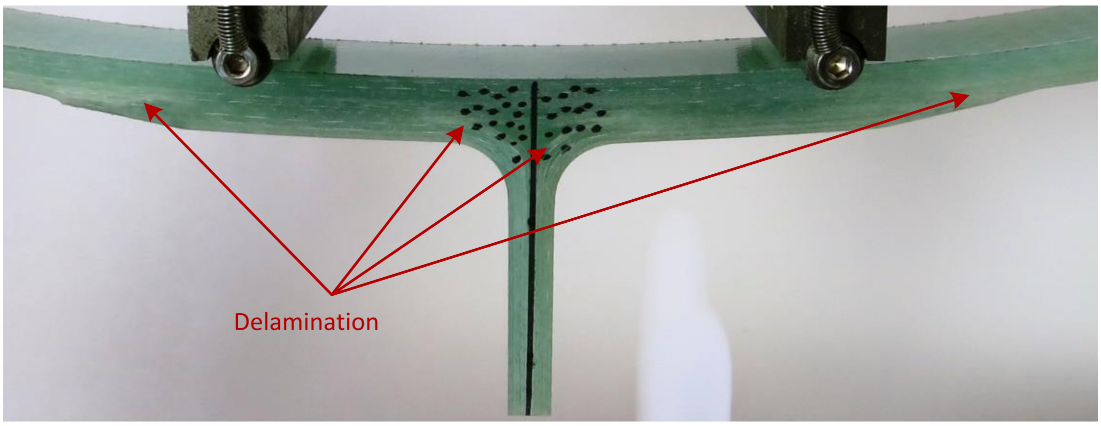
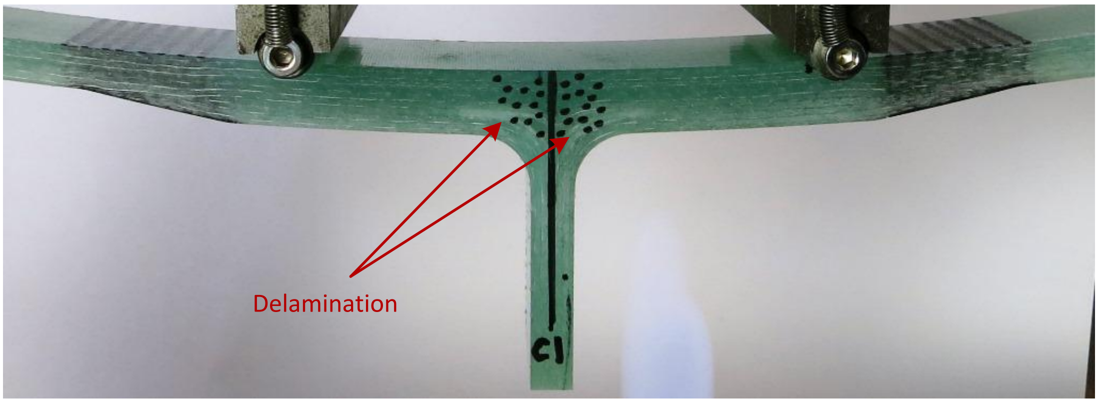


Figure 8: First failure load-displacement plot for skin-stringer tests.



(a) Control



(b) Stringer transition and skin tufted

Figure 9: Delamination observed at first load drop during four-point bend testing.

9 CONCLUSIONS

The trigger mechanisms that initiate delamination in a T-stiffened skin-stringer joint were examined in four-point bending. Delamination initiated at the skin-stringer tip, and the flange to web transition within the stringer itself. Tufting was used to reinforce the stringer tip using two approaches: adding tufts to the transition region between the skin and stringer flange, and tufting this transition and the skin area adjacent to the stringer tip. Both methods were successful at mitigating the delamination between the skin and the stringer flange, but the additional tufts in the skin served to increase the stiffness of the joint and the peak load above simply tufting the skin to flange transition. Tufting was unable to fully mitigate the damage within the joint, as delamination initiated within the stringer, at the flange to web transition, resulting in web-splitting failure of the joint. Incorporating tufts in this area will be evaluated as a mechanism to further mitigate delamination and damage propagation within composite joints.

ACKNOWLEDGEMENTS

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) under the Impact Acceleration Award scheme at the University of Bristol, in partnership with the National Composite Centre (NCC). The authors would like to thank Emily Withers and Jamie Hartley for their assistance during panel manufacturing.

REFERENCES

1. R. Pearson, A. Yee. Toughening mechanisms in thermoplastic-modified epoxies: 1. Modification using poly (phenylene oxide). Polymer (Guildf)., vol. 34, no. 17, pp. 3658–3670, 1993.
2. Hedrick JL, Yilgör I, Wilkes GL, McGrath JE. Chemical modification of matrix Resin networks with engineering thermoplastics - 1. Phenolic hydroxyl terminated poly(aryl ether sulfone)-epoxy systems. Polymer Bulletin. 1985;13(3):201-8.
3. Pascal T, Bonneau JL, Biolley N, Mercier R, Sillion B. Approach to improving the toughness of TGMDA/DDS epoxy resin by blending with thermoplastic polymer powders. Polymers for Advanced Technologies. 1995;6(4):219-29.
4. Dransfield K, Baillie C, Mai Y-W. Improving the delamination resistance of CFRP by stitching—a review. Composites Science and Technology. 1994;50(3):305-17.
5. Cartié DDR, Dell'Anno G, Poulin E, Partridge IK. 3D reinforcement of stiffener-to-skin T-joints by Z-pinning and tufting. Engineering Fracture Mechanics. 2006;73(16):2532-40.
6. Dell'Anno G, Treiber JWG, Partridge IK. Manufacturing of composite parts reinforced through-thickness by tufting. Robotics and Computer-Integrated Manufacturing. doi: 10.1016/j.rcim.2015.04.004.
7. Osmiani C, Mohamed G, Allegri G, Partridge IK. Exploring the influence of micro-structure on the mechanical properties and crack bridging mechanisms of fibrous tufts. Proceeding of the 7th International Conference on Composites Testing and Model Identification CompTest 2015, Madrid, Spain, April 8-10 2015.
8. Bertolini J, Castanié B, Barrau JJ, Navarro JP. An experimental and numerical study on omega stringer debonding. Composite Structures. 2008;86(1-3):233-42.
9. Greenhalgh E, Garcia MH. Fracture mechanisms and failure processes at stiffener run-outs in polymer matrix composite stiffened elements. Composites Part A: Applied Science and Manufacturing. 2004;35(12):1447-58.
10. Theotokoglou EE, Moan T. Experimental and numerical study of composite T-joints. Journal of Composite Materials. 1996;30(2):190-209.
11. Krueger R, Cvitkovich MK, O'Brien TK, Minguet PJ. Testing and Analysis of Composite Skin/Stringer Debonding under Multi-Axial Loading. Journal of Composite Materials. 2000;34(15):1263-300.