INTERLOCKING THIN-PLY REINFORCEMENTS FOR THE IMPROVEMENT OF CAI STRENGTH

John-Alan Pascoe[1], Soraia Pimenta[2], Silvestre T. Pinho[1]

[1]Department of Aeronautics, Imperial College London, South Kensington Campus, London, SW7 2AZ, United Kingdom
Email: j.pascoe@imperial.ac.uk, silvestre.pinho@imperial.ac.uk,
Web page: `http://tinyurl/pinholab`
[2]Department of Mechanical Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ, United Kingdom
Email: soraia.pimenta@imperial.ac.uk

Keywords: Damage tolerance, Compression after impact, Interlaminar reinforcement, Thin-ply

Abstract
A new reinforcement concept for improving compression after impact strength of carbon fibre reinforced polymers is explored. The concept consists of manufacturing interlocked reinforcement units from thin-ply prepreg, which are inserted at the interlaminar interfaces within a regular ply-thickness laminate. Compression after impact tests following ASTM standards were performed on both reinforced and baseline specimens. The reinforced specimens showed a 11.4 % reduction in post-impact delamination area. The strength results will be presented at the conference.

1. Introduction

Impacts on composite laminates can result in large reductions in compressive strength and stiffness. Yet the damage caused by impacts can be difficult to detect. Consequently, a high residual strength is needed to ensure safety of a structure, and the compression after impact (CAI) strength may be more critical as a design allowable than the undamaged strength.

Previous researchers have therefore sought to improve CAI strength through, e.g., increasing matrix toughness [1], interlaminar toughening [1], or translaminar reinforcement [2]. These methods have in common that they seek to improve CAI strength by limiting the growth of delaminations, during both the initial impact event, and the subsequent compression.

In this work, load paths are created by means of interlocked thin-ply reinforcement units, placed between the plies of a regular ply-thickness laminate. This paper will first discuss the reinforcement concept in more detail, and then present the results of the impact tests, showing the improvement to impact resistance. The results of the compression tests and the improvement to CAI strength achieved by the concept will be presented at the conference.

2. Reinforcement concept

The reinforcement concept used in this work consists of placing interlaminar reinforcement units between the plies of a regular fibre reinforced polymer (FRP) laminate. These units are placed at each interface at which there is a fibre orientation mismatch.

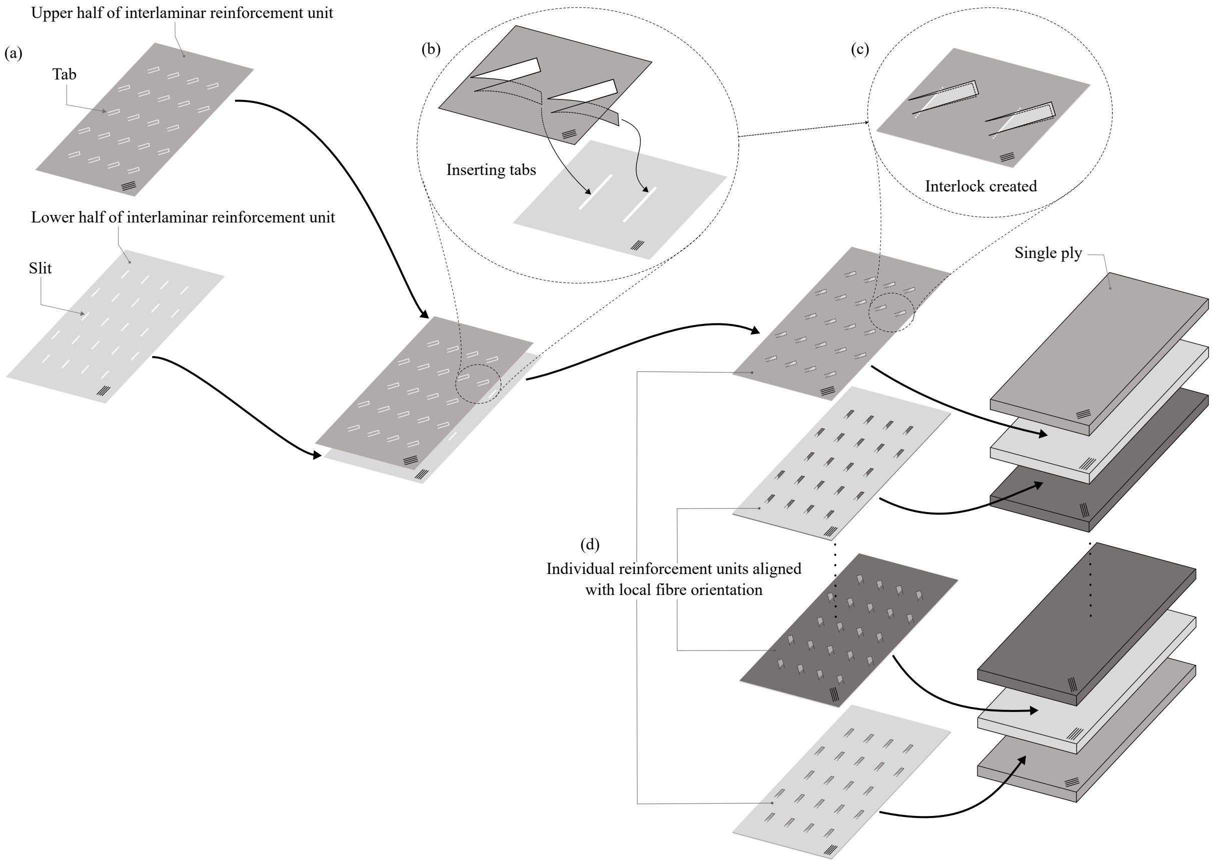

Figure 1. Schematic illustration of the reinforcement concept and the manufacturing process, showing (a) the separate components of the interlock units, (b) the insertion of the tabs, (c) the interlocked configuration, and (d) the insertion of the reinforcement units during the lay-up process.

This concept was inspired by a different crack arrester concept developed by Minakuchi and Takeda [3, 4] for use in adhesive bonds. In the Minakuchi concept, regular thickness composite layers are interlocked to form a single arrester location, which is inserted in an adhesive bondline. Instead, in the present work, very thin reinforcement units are inserted between plies of a regular composite laminate to promote fibre bridging. Rather than arresting a crack at a specific location, as in the Minakuchi concept, these reinforcement units work by preserving load paths between adjacent plies, at multiple locations.

Each reinforcement unit is built up from two thin-ply prepreg layers, with fibre orientations differing by 45°. Rectangular tabs are cut into the top layer (i.e. the layer closest to the impacted face of the specimen), and slits are cut into the bottom layer (Fig.1a). The slits, and the long axes of the tabs, are aligned parallel to the fibre direction in the respective layer. The two layers are placed together, and the tabs are inserted through the slits (Fig.1b), producing an interlocked reinforcement unit (Fig.1c). Multiple reinforcement units with different orientations are produced and inserted at the interfaces of a regular ply-thickness composite lay-up (Fig.1d).

The orientations of the reinforcement units are chosen such that the fibre orientation of the top thin-ply layer matches the orientation of the regular ply layer above the reinforcement. Similarly, the fibre orientation of the bottom thin-ply layer matches the orientation of the regular ply layer below the reinforcement. In this way it is ensured that all fibre orientation mismatches occur at the mid-planes of the reinforcement units.

During an impact, delaminations will initiate at the interfaces at which there is a fibre angle mismatch [5, 6], i.e. at the mid-planes of the reinforcement units. As these delaminations grow, they will bypass the tabs, leaving a load path from above the top layer of the reinforcement, to below the lower layer. Thus there are still connections between the two plies adjacent to the reinforcement unit, via the tabs. These connections will bridge the delamination, increasing the overall fracture toughness. Additionally the intact connections may stabilise the laminate against local buckling during the post-impact compression loading, resulting in a higher residual strength.

3. Specimen configurations and manufacturing

In this research, two specimen configurations were tested: baseline (BL) and reinforced (RE). The RE specimens had the same lay-up as the BL specimens, but interlocked reinforcement units were placed between the regular thickness plies, rather than non-interlocked thin-plies.

For both configurations, Cytec MTM28-1 / T800 prepreg (nominal ply thickness 125 μm) was used for the regular thickness layers, and SK Chemicals Skyflex USN 020A (T700 carbon fibre / K51 epoxy) prepreg (nominal ply thickness 25 μm) was used as thin-ply material.

The BL specimens were manufactured by a standard hand lay-up process. For the RE specimens, the reinforcement units were laid-up and interlocked separately first, and then placed at the appropriate locations during a hand lay-up of the final laminate.

In accordance with the ASTM standards [7, 8] the specimens were rectangular, with a nominal length of 150 mm and a nominal width of 100 mm. The baseline specimens had an average thickness of (4.51 ± 0.07) mm. The average thickness of the reinforced specimens was (4.55 ± 0.05) mm.

Five specimens of each configuration were subjected to both impact and compression tests, as will be described below.

4. Impact tests

Impact tests were conducted in accordance with ASTM standard D7136 [7] on an Instron CEAST 9350 drop-tower. The specimens were impacted with 6.7 J/mm (energy per unit laminate thickness), using a hemispherical impactor with a diameter of 16 mm and a mass of 5.392 kg. After the impact test the specimens were C-scanned with a TechniTest Triton 1700 TT ultrasonic scanner, using a 10 MHz transducer in pulse-echo mode.

A typical C-scan for both the baseline specimens and the reinforced specimens is shown in figure 2. The average projected area was (1066.0 ± 46.0) mm^2 for the baseline specimens and (945.0 ± 72.7) mm^2 for the reinforced specimens, as can be seen in figure 3. This represents a reduction of 11.4 %.

5. Compression tests

The compression tests followed ASTM standard D7137 [8], using an Instron 250 kN test frame. Testing was performed in displacement control, with a load rate of 1.25 mm/min. In accordance with the standard the specimen was considered to have failed when a load drop of more than 30% was recorded. The results of the compression tests will be presented at the conference.

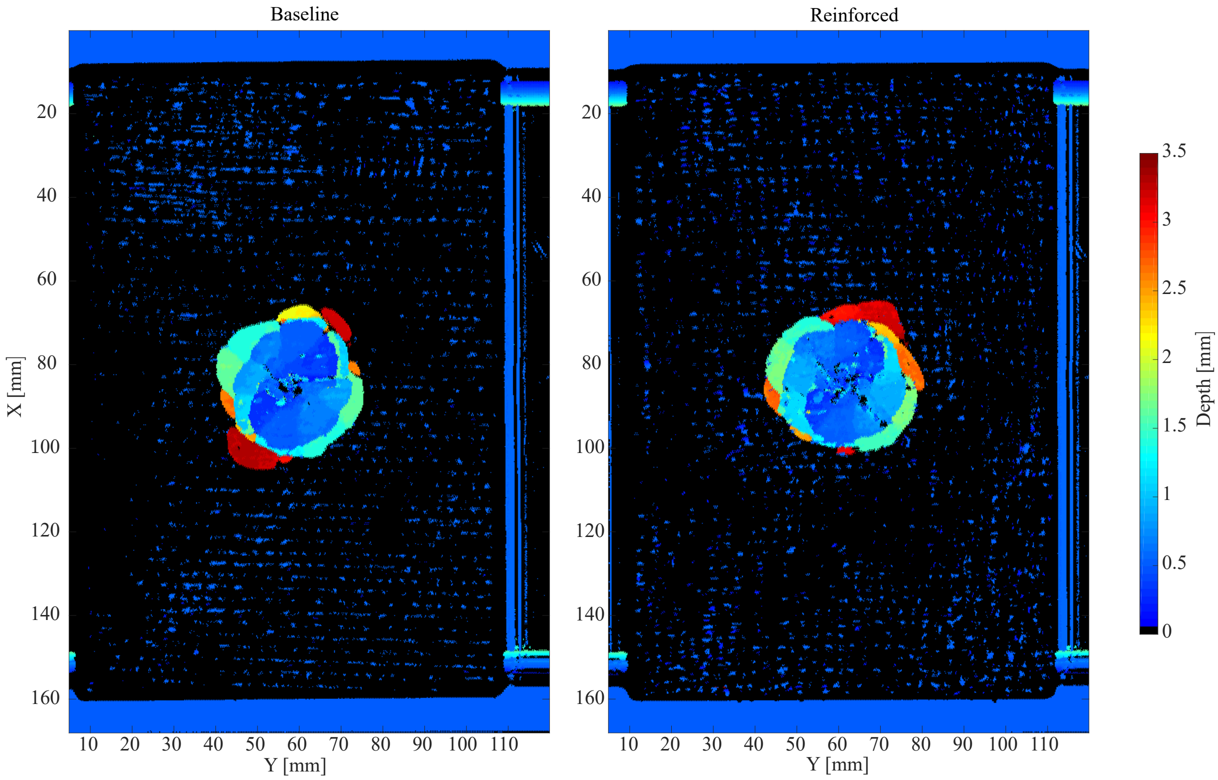

Figure 2. Typical post-impact C-scan images of a baseline (left) and reinforced (right) specimen. The X-axis corresponds to the 0° fibre direction, which was also loading direction during the compression tests.

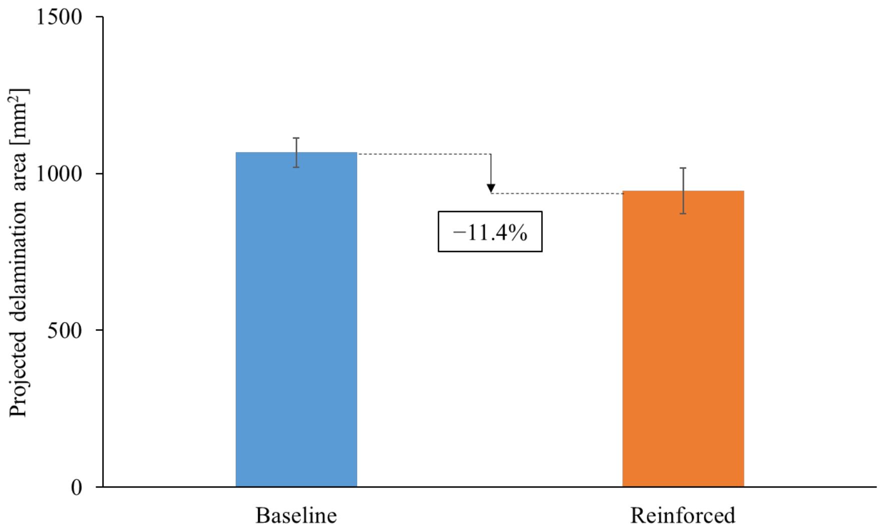

Figure 3. Projected delamination area for the baseline and reinforced specimens, as measured from the C-scans. The error bars show the standard deviation.

6. Conclusion

A new reinforcement concept for increasing CAI strength was proposed, manufactured, and tested. The concept consists of maintaining load paths between the regular ply-thickness layers, which survive the impact. These reinforcements may act as crack bridges, increasing fracture toughness, and thereby resistance to delamination.

Laminates containing interlocked reinforcement units were compared to baseline specimens with non-interlocked interlaminar thin-plies. The reinforced specimens exhibited a 11.4 % reduction of projected delamination area post-impact.

Acknowledgements

Funding from the EPSRC under grant EP/M002500/1 is gratefully acknowledged. S. Pimenta acknowledges the Royal Academy of Engineering for her Research Fellowship on *Multiscale discontinuous composites for large scale and sustainable structural applications* (2015-2019).

References

[1] N. H. Nash, T. M. Young, P. T. McGrail, and W. F. Stanley, "Inclusion of a thermoplastic phase to improve impact and post-impact performances of carbon fibre reinforced thermosetting composites - A review," *Materials and Design*, vol. 85, pp. 582–597, 2015.

[2] L. Dickinson, G. Farley, and M. Hinders, "Translaminar Reinforced Composites : A Review," *Journal of Composites Technology & Research*, vol. 21, no. 1, pp. 3–15, 1999.

[3] S. Minakuchi, "Fiber-Reinforcement-Based Crack Arrester for Composite Bonded Joints," in *Proceedings of the 20th International Conference on Composite Materials*, Paper 2118-4, 2015.

[4] S. Minakuchi and N. Takeda, "Stopping Fatigue Crack in Composite Bonded Joint Using Interlocked Fiber Feature," in *15th European - Japanese Symposium on Composite Materials*, 2017.

[5] S. Abrate, *Impact on Composite Structures*. Cambridge: Cambridge University Press, 1998.

[6] D. Bull, S. Spearing, and I. Sinclair, "Observations of damage development from compression-after-impact experiments using ex situ micro-focus computed tomography," *Composites Science and Technology*, vol. 97, pp. 106–114, jun 2014.

[7] ASTM D7136/D7136M-05, *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event*. West Conshohocken, PA: ASTM International, 2005.

[8] ASTM D7137/D7137M-07, *Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates*. West Conshohocken, PA: ASTM International, 2007.