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The effect of stitch distribution on Mode I delamination toughness of stitched laminated composites – experimental results and FEA simulation

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Abstract

In this paper, a tabbed double cantilevered beam test is performed on Vectran® stitched laminated composites with varying stitch distributions. The woven carbon fibre plies were laid-up in a symmetrical manner $[0, \pm 45, 90]_2$, then stitched in dry preform state followed by a resin film infusion stage. To prevent the stitched specimens from failing in flexure, thick aluminium reinforcing tabs were adhesively bonded to either side of the composite specimen, along with loading blocks. An INSTRON 5567 testing machine was used to test the specimens at a crosshead speed of 0.5 mm/min with crack lengths, crack opening displacements and peak load data being recorded after the crack front had propagated several millimetres. A variation of the compliance method was used to post process the test data. It is revealed that for stitched specimens with identical stitch densities but different stitch distributions, there exists significant variations in critical strain energy release rates, G_{Ic}. A 2-node beam and 4-node plate finite element analysis was conducted to model the TDCB experiment with a special 2-node axial, tension only, rod element used to discretely simulate the stitches. The FEA results support the experimental findings identifying stitch distribution as a key parameter in determining the improvement that stitching provides in bridging Mode I delaminations.

Keywords: Tabbed double cantilevered beam; Stitching; Mode I; Laminated composites

1. Introduction

Through-the-thickness reinforcement by way of stitching [1–4] and z-pinning [5–8] has been well documented to increase the Mode I delamination toughness of laminated composites by providing bridging traction forces within the delamination zone. To this end, stitching and z-pinning of laminated composites have significant commercial applications particularly in the aerospace industry in the way of increased damage tolerance, reduction in free edge delamination, structural joining and an overall reduction in component weight.

To delay progressive delamination and subsequent catastrophic failure, in recent decades, laminated composites have been reinforced in the through-the-thickness (TTT) direction by means of stitching [9] and z-pinning reinforcement [5]. Z-pinning as it has come to be known involves the mechanical insertion of solid or fibrous independent pins/rods aligned in the TTT direction of the laminate. Stitching of laminated composites is similar to its clothing/textile counterpart, differing only in stitch type, where a modified lock stitch is used. Stitching can be interconnected or

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independent with the latter requiring an extra machining process to shear off the surface loop of the continuous stitch.

Considering the growing occurrence of composites in weight critical applications over the past two decades, the importance for further development in the way of numerical models for analysing laminated composites has grown enormously. This is particularly pertinent in the case of composites reinforced through-the-thickness by stitching, z-fibres or short metallic rods. In recent times there have emerged some stitching and z-fibre models that aim to better characterize the effects of through-the-thickness reinforcement. These include independent and interconnected stitch models proposed by Jain and Mai [10], z-fibre models by Cox [11,12], a z-rod model by Tong and Sun [8], and a finite element simulation for 3D orthogonal interlocked fabrics composites by Tanzawa et al. [13].

Jain and Mai [10] produced an analytical model which uses a continuously distributed equivalent load within the crack wake, representative of discrete stitching. The independent stitch behaves analogous to a rope that is capable of elastic stretching and pullout. The interconnected stitch model is fixed at the substrate beam surface and is able to stretch and rupture. Sun et al. [14] developed a finite element model using the analytical stitch models proposed by Jain and Mai [10]. The model used discrete stitches but demonstrated good correlation with the results exhibited by Jain et al. [10] by reducing the discrete stitch pitch distance to a small enough level so as to simulate a uniform bridging traction.

Presently there is significant empirical [15] and analytical [9] data available supporting the positive contribution of TTT reinforcement in bridging delamination cracks, with many researchers reporting the importance of stitch fibre diameter, stitching density and interfacial shear stress. Recent finite element analysis (FEA) conducted by Sun et al. [14] has shown that stitch distribution is an influential parameter when predicting the improvement in Mode I delamination toughness. The research showed that for identical stitch densities with varying stitch distributions, the resulting *R*-curve behaviour could be highly dissimilar. Liu [16] concluded through compression after impact (CAI) experiments that stitch pattern can change the shape of the impending delamination but not the size of the affected area. Tanzawa et al. [13] also conducted finite element simulations of 3D orthogonal composites and revealed that fibre ‘‘slack’’ contributed to the bridging effect by providing a longer bridging zone. The current state of FEA, in regards to the modelling of stitched composites, is a growing field with much room for further research particularly in the area of stitch model development.

In this paper, Mode I delamination toughness experiments are conducted on stitched laminated woven carbon fibre modified double cantilever beam (TDCB). Both plain (straight interconnected) and zigzag (interconnected) stitching patterns are used with all specimens having the same stitch density but varying stitch distributions. A finite element beam and plate model analysis, using a discrete interconnected stitch element, is conducted to verify the experimental data. Results of this analysis are in good agreement with the empirical findings. It is clear that the beam and plate finite element schemes are capable of generating accurate G_{IR}–Δa and load–crack open displacement (COD) curves for stitched TDCB specimens. Furthermore, stitch distribution is established as a critical parameter when determining the improvement in Mode I delamination toughness for stitched TDCB specimens.

2. Experiment – materials, manufacture, testing and analysis

2.1. Material systems

The ASTM standard for testing Mode I delamination toughness requires unidirectional laminae usually with a small percentage of fibres holding the ply together. However, unidirectional preform laminae's are highly unsuited for stitching since the transverse fibres required to hold the stitches in place are not present in great quantities. For this reason we used a woven fabric system, Hexcel's G926 5-harness HTA 0.32 mm thick woven carbon fibre fabric, with 7% by weight EB6 binder on both surfaces (to assist in preforming) and 51% warp and 49% weft rovings in a satin weave, refer to Table 1.

Developed especially for the aviation industry, for use in aircraft primary structures, Hexply® M36 high performance film resin was chosen as the preferred matrix for the test specimens.

The stitching yarn was Vectran® high strength (HS) liquid crystal polymer (LCP) fibre. Exhibiting exceptional strength, rigidity, low moisture absorption, excellent flex/fold characteristics and high abrasion resistance, this man-made fibre is ideal for stitching thick composite panels. The yarn was a 2 ply 1500 denier yarn with 2.5 TPI and each filament having a measured diameter of 23 μm or 5 DPF. Twisting of the stitching yarn binds the fibres together creating a circular cross-section as well as reducing the snubbing that occurs as the thread is pulled through the eye of the needle. Along with the woven fabric, this combination provides a basis for real world comparison.

2.2. Manufacturing method

The composite laminate was laid-up symmetrically $[0°, \pm 45°, 90°]_2$ in a dry preform state in preparation for

Table 1
Material properties

Property	Vectran®	HexPly® M36 Resin	Hexcel G926
Density (g/cm^3)	1.4	1.17	1.76
Tensile strength (MPa)	2840 (min)–3210 (max)	81	3530
Tensile modulus (GPa)	64.8 (min)–72.4 (max)	3.5	230
Temperature (°C)	330 (mp)	211 (Tg)	–
Poisson's ratio	–	0.42	–
Toughness K_{Ic} MPa$\sqrt{m}$	–	0.9	–
Toughness G_{Ic} J/m^2	–	190	–