Composites Science and Technology 118 (2015) 141–153

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Further investigation of Delamination Reduction Trend for stitched composites

K.T. Tan [a,*], A. Yoshimura [b], N. Watanabe [c], Y. Iwahori [b], T. Ishikawa [d]

[a] Department of Mechanical Engineering, The University of Akron, Akron, OH 44325-3903, USA
[b] Advanced Composite Research Centre, Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka, Tokyo 181-0015, Japan
[c] Department of Aerospace Engineering, Tokyo Metropolitan University, 6-6 Asahigaoka, Hino, Tokyo 191-0065, Japan
[d] Department of Aerospace Engineering, Nagoya University, Furoh, Chikusa, Nagoya 464-8603, Japan

A R T I C L E I N F O

Article history:
Received 23 April 2015
Received in revised form
5 August 2015
Accepted 26 August 2015
Available online 4 September 2015

Keywords:
Polymer-matrix composites (PMCs)
Delamination
Statistics
Non-destructive testing
Stitching

A B S T R A C T

This paper seeks to further investigate a recently proposed novel empirical-based *Delamination Reduction Trend* (DRT) for stitched composites. The DRT is capable of predicting the effective reduction in impact-induced delamination area due to the influence of stitching. DRT simply relates two parameters: normalised delamination area and stitch fibre volume fraction, to characterize the effectiveness of stitching in impact damage suppression. In this work, quasi-static indentation (QSI) test is performed on stitched composites with the aim to offer new observations, provide validations and understand limitations in DRT. Test data coupled with experimentally observed damage mechanisms reveal limitations of DRT, particularly across two regions: first, when damage is initiated and delamination growth has not been developed; second, when delamination propagation is influenced by boundary conditions and saturation of delamination damage has occurred. Validation of DRT is demonstrated in domain outside of these regions. The investigation is further analysed by statistical approach using a three-factorial design of experiments (DoE). The main influence and coupling interaction of stitch density, stitch thread thickness and indentation displacement on indent-induced delamination area are established and discussed. Graphical and statistical results provide further insights and validation to DRT. The novelty of this work lies in showing validation and understanding limitation of DRT for its effective use and accurate prediction of delamination damage in stitched composites.

1. Introduction

The main advantage of carbon fibre reinforced polymer (CFRP) composites, in terms of their high strength-weight ratio and high stiffness-weight ratio, is counterpoised by their major weakness in low interlaminar strength. One effective method to overcome this key drawback in CFRP laminates is by through-the-thickness stitching. The resurging interest in the use of stitching to increase delamination resistance and improve damage tolerance of laminated composites has been evident in many recent works [1–12]. Locally, stitching works by significantly reducing the driving force for propagation of the delamination crack and creating closure tractions acting across the crack length [13]. Structurally, stitching parameters, like stitch density and stitch thread thickness, influence the effectiveness of stitching on delamination resistance, and much effort has been deployed to investigate these effects [10–12,14].

Tan et al. [15] recently proposed an empirical-based *Delamination Reduction Trend* (DRT) for stitched composites. The DRT is able to predict the effective reduction in impact-induced delamination area due to the influence of various stitch parameters. DRT is developed based on an extensive series of low-velocity impact (LVI) tests using specimens of different laminate thicknesses, stitch densities and stitch thread thicknesses, subjected over a range of impact energy levels. All the test data eventually resolved to a simple DRT observation that merely relates two parameters: normalised delamination area ($Delam_{Norm}$ – which is calculated by dividing the impact-induced delamination area of stitched specimen over the delamination area of unstitched counterpart at the same test condition), and stitch fibre volume fraction (V_{ft} – the

* Corresponding author.
E-mail address: ktan@uakron.edu (K.T. Tan).

http://dx.doi.org/10.1016/j.compscitech.2015.08.019

percentage of stitch thread fibre in the material: a parameter that couples stitch density and stitch thread thickness) to characterize the effectiveness of stitching in impact damage suppression (Fig. 1). DRT evidently shows a bi-linear behaviour: first, an initial linearly decreasing relationship of $Delam_{Norm}$ with V_{ft}; and second, a plateau which indicates maximum delamination area reduction limit of 40%–50% by stitching (Fig. 1). The physical-based explanation for the bi-linear behaviour is given in Ref. [15]. Although DRT seems to suggest that the effect of impact energy is independent of $Delam_{Norm}$ and V_{ft}, one can only assume the validity of DRT over the impact energy range (6.7–60.8J) performed in the work [15]. It, however, remains unclear what limitations does DRT hold, and under what test conditions will the predictions of DRT be invalid and inaccurate.

This paper aims to further investigate the DRT using Quasi-Static Indentation (QSI) test. QSI test is a systematic experimental test procedure whereby the specimen is progressively indented, and the delamination growth is gradually and carefully measured. Previous works have shown that damage in QSI test is comparable to impact damage in LVI test [16–18]. The main advantage of QSI test is the ability to capture the full scope of impact behaviour, from damage initiation phenomenon to delamination progression characteristics, using the same test specimen. Performing a single QSI test is analogous to carrying out numerous LVI tests to the extent of covering a complete spectrum of impact energy levels, which is experimentally costly and practically unfeasible. The objective of this study is to offer new observations, provide validations and understand limitations to DRT in stitched composites using QSI test, which would otherwise be unnoticed and unobserved by the actual conduct of LVI tests [19,20]. In this work, specimens, stitched with various stitch configurations, are quasi-statically loaded and unloaded at 0.5 mm incremental indentation depth to observe delamination propagation. The delamination damage inside the test laminate is examined using two independent techniques, namely the ultrasonic C-scan analysis and the X-ray radiography, to accurately confirm the delamination size. The delamination size reductions due to stitching are analysed and discussed based on the effect of stitch density (*SD*) as well as through-the-thickness stitch fibre volume fraction (V_{ft}). Results are used to compare with the recently proposed DRT. A statistical approach using the Factorial Design of Experiments (DoE) is further employed to better analyse the individual and joint effects of stitch density and stitch thread thickness on delamination propagation, with the aim to further understand the DRT.

2. Experimental procedure and analysis

2.1. Test specimens

The specimens were made using T800SC-24K (Toray Industries) carbon fibre fabric of 20-ply $[+45/90/-45/0/0/+45/90/90/-45/0]_S$. The linear density of Vectran stitch threads used in this study is 200 or 400 denier (stitch thread cross-sectional area, S_{Area} of 0.0158 mm^2 and 0.0316 mm^2 respectively), with a stitch space S_S and stitch pitch S_P of 3 mm × 3 mm (densely stitched) or 6 mm × 6 mm (moderately stitched). Vectran is a high-performance multifilament yarn spun from liquid crystal polymer (LCP). It is the only commercially available melt-spun LCP fibre in the world. Vectran fibre exhibits exceptional strength and rigidity. Vectran is selected as the stitch fibre because, besides having comparable properties with Kevlar, it is more superior due to its very low propensity to absorb moisture and performs better in interlaminar strengthening of stitched composites [21]. The type of stitch used is the Modified Lock stitch. After the stitching process, resin transfer moulding (RTM) technique, using resin XNR/H6813, was adopted to consolidate the composite. Specimens of 100 mm width and 150 mm length were then cut out from a mother plate using a diamond wheel cutter. The average specimen plate thickness is 4.1 mm. All specimens are physically examined for any poor-resin regions and ultrasonic C-scanned for any internal delamination to ensure that they are free from any manufacturing related defects. More details on the material preparation can be found in authors' earlier works [10,11]. Stitch density, *SD* and through-thickness stitch fibre volume fraction, V_{ft} of the stitched specimens can be calculated using Equations (1) and (2). The integer '2' in Equation (2) represents two stitch yarns (a pair of stitch yarn) in the thickness direction for each stitch loop formed at one side of the stitched laminate. The stitching configuration and cross sectional diagram used in this study are schematically illustrated in Fig. 2.

$$SD = \frac{1}{S_P \times S_S} \tag{1}$$

$$V_{ft} = SD \times S_{Area} \times 2 \times 100\% \tag{2}$$

2.2. Quasi-static indentation test and delamination propagation

Quasi-static indentation (QSI) test was performed using Instron 5582 test machine (100 kN load cell) with a displacement rate of

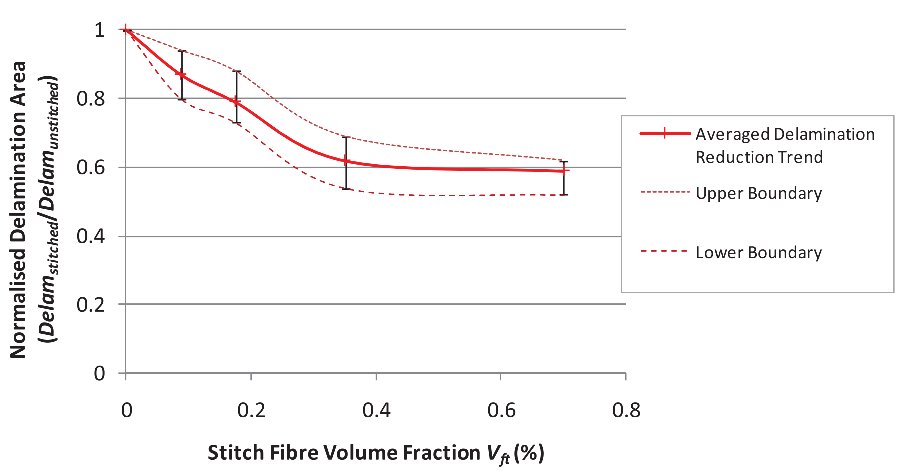

Fig. 1. Delamination Reduction Trend (DRT) for stitched composites [15].