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Effect of stitch density and stitch thread thickness on damage progression and failure characteristics of stitched composites under out-of-plane loading

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ABSTRACT

In this paper, the damage progression and failure characteristics of stitched composites under out-of-plane loading are experimentally investigated. Test specimens, stitched with various stitch densities and stitch thread thicknesses, are studied using quasi-static indentation test. Test specimens are loaded and unloaded in 0.5 mm incremental indentation displacement to examine for damage phenomena using non-destructive inspection techniques namely ultrasonic C-scan, X-ray radiography and X-ray micro-computed tomography to elucidate complex damage mechanisms and fracture behavior. Recorded test history of load–displacement curves indicate that damage progression can be characterized into three stages: *damage initiation, damage propagation and final damage failure*. Results show that damage initiation occurs at a lower load in stitched composites due to the presence of resin-rich regions which act as crack initiation sites. X-ray radiography convincingly shows that stitch-induced matrix crack lines are joined between stitch loops, being particularly evident in densely stitched composites. During damage propagation, stitching becomes highly effective in suppressing delamination growth, resulting in stitched laminates having much smaller delamination area compared to unstitched laminates, and the rate of delamination growth being inversely related to stitch density. It is found out that final failure is distinguished by a sharp load drop in the load–displacement curve. It is revealed that the final failure load increases with increasing stitch fiber volume fraction. The final failure mechanism in unstitched and moderately stitched composite is mainly delamination failure; while densely stitched composite failed by indenter penetration comprising of in-plane fiber fracture and matrix crushing. Energy absorption throughout the quasi-static indentation process is presented and discussed. This work provides novel insight to the damage progression and damage penetration of stitched composites.

1. Introduction

Despite the numerous advantages of using fiber-reinforced composite materials in structural applications, the primary weakness of laminated composites is their poor interlaminar strength. Driven by the need to overcome this major drawback and significantly improve the delamination resistance of composite structures, researchers over the world are actively seeking effective interlaminar reinforcement techniques. Stitching has been proven to be successful in resolving delamination susceptibility in composite materials [1,2]. Stitching increases the delamination resistance by reducing the crack opening displacement in mode I loading and resisting crack sliding displacement in mode II [3–5]. Bridging force offered by stitches significantly increases the ultimate strength of the material through high energy absorption in the process of fiber fracture and frictional pull-out [6]. Stitching arrests and improves crack closure by shielding the crack tip from the full effect of the crack opening stress [7,8].

Numerous literatures published over recent years are clear evidence that there has been a resurging interest in the use of stitching to improve the impact resistance and damage tolerance of composites [9–16]. Researchers have evidently shown that stitching can significantly reduce impact-induced delamination area by comparing stitched and unstitched specimens [13–16]. Tan et al. [9,10] further studied the influence of stitch parameters and investigated the effect of stitch density and stitch thread thickness on low velocity impact damage and compression after impact strength of stitched composites. It has been found out that both stitch density and stitch thread thickness have considerably effect on the damage response, mechanisms and behavior of stitched composites due to out-of-plane impact loading. The availability

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of many other published literatures on impact damage of stitched composites allows general understanding on the overall effectual performance of stitching [9–16]. However, the effect of stitch density and stitch thread thickness on damage progression of stitched composites due to out-of-plane loading has not been investigated. Damage in composite materials is an extremely complex phenomenon that comprises of multiple failure modes: intra-laminar matrix cracks, inter-laminar delamination, fiber pull-out and fiber breakage. With the inclusion of stitch threads, the damage behavior of stitched composite is further complicated. To better utilize stitching in composite structures, it is important to understand how stitch parameters, like stitch density and stitch thread thickness, affect the various stages of damage progression: from damage initiation, to damage propagation, and eventually leading to final damage failure.

Quasi-static indentation (QSI) test has been used by researchers to investigate the mechanical response and energy absorption of sandwich panels [17] and composite laminates [18]. QSI test provides clear understanding of damage mechanisms at various stages of damage progression [19]. QSI test results also offer similar observations with that obtained from low velocity impact test, due to analogous impact and boundary conditions. Aoki et al. [20] showed that both the low-velocity test and static indentation test gave the same results. Sun and Jih [21] demonstrated that a quasi-static analytical model agrees well with experimental low-velocity impact test result. Researchers also use numerical simulation of quasi-static indentation test to validate and predict low-velocity impact test of stitched composites [13,22]. Besides validating low velocity impact test results, QSI test data further reveal additional observations, like damage progression, change in damage mechanisms and modes of energy absorption during the impact event, that are not being captured by the low velocity impact test [23]. However, it is worth noting that the potential limitations of QSI are that the tests are time-demanding, and the quasi-static approach is based on the assumption that the specimen has sufficient time to response to the indentation load, which might be slightly different in the actual impact event. Researchers have studied the quasi-static response of stitched non-crimp fabrics due to in-plane tension, out-of-plane compression and 3-point bending [24]. Researchers also worked on quasi-static testing of stitched laminated panels/beams subjected to bending leading to understanding of the influence of stitching on damage characteristics and delamination toughness, mode I/II or mixed mode [25–30]. However, the study on the effect of both stitch density and stitch thread thickness on the indentation test of stitched composites is currently lacking. QSI test on stitched composites would provide physical observations of the progressive damage phenomenon and fracture behavior of stitched composites, forming the basis for realistic computational modeling that closely resembles experimentally observed behavior.

This paper aims to investigate and study the effect of stitch density and stitch thread thickness on damage progression and failure characteristics of stitched composites. Stitched composites are subjected to out-of-plane loading using quasi-static indentation test. By loading and unloading test specimens at 0.5 mm incremental indentation displacement, the quasi-static response behavior, affected by stitch density and stitch thread thickness, is characterized by recording specimen force–displacement history graphs. Various stages of damage progression: damage initiation, damage propagation and final damage failure, are distinctively identified. Relationships of stitch parameters with damage initiation force and final failure load are established. Non-destructive inspection techniques like ultrasonic C-scan, X-ray radiography and X-ray micro-computed tomography (μCT) are employed to observe and elucidate damage phenomenon and fracture mechanisms during damage progression. Finally, energy absorption during the quasi-static indentation process is evaluated and discussed, with the objective to understand and compare the energy consumption by different failure mechanisms on varying stitch density and stitch thread thickness. Results from this study seek to reveal novel insights to better understand the way stitching influences damage initiation and damage penetration due to out-of-plane loading, which are currently lacking in the literatures. Although similar damage inspection techniques are used in this study, this work on damage progression supplements earlier works by the authors' group to better understand the performance of using stitching as an interlaminar reinforcement technique.

2. Experimental details

2.1. Material preparation

Test specimens were made using T800SC-24K (Toray Industries) carbon fiber fabric of 20-ply $[+45/90/-45/0/0/+45/90/90/-45/0]_S$. Through-thickness stitching was performed using Vectran fiber. Vectran, a relatively new fiber material, is selected as the stitch fiber because, besides having comparable properties with Kevlar, it is more superior in terms of its very low propensity to absorb moisture and performs better in interlaminar strengthening of stitched composites [31]. Vectran stitch fiber, of linear density 200 denier or 400 denier (cross-sectional area, S_{Area} of 0.0158 mm^2 and 0.0316 mm^2 respectively), is inserted at an equal stitch pitch, S_P and stitch space, S_S of 3 mm or 6 mm. The type of stitch used is the modified lock stitch. Unstitched specimens are manufactured by isolating a coupon size area from stitching. In this way, the difference in thickness and fiber contents of unstitched and stitched specimens is kept at minimum.

Stitch density, SD and through-thickness stitch fiber volume fraction, V_{ft} of the stitched specimens can be calculated using the following equations:

$$SD = \frac{1}{S_P \times S_S} \quad (1)$$

$$V_{ft} = SD \times S_{Area} \times 2 \times 100\% \quad (2)$$

where S_P is the stitch pitch defined by the distance between two adjacent stitches in the same row, S_S is the stitch space defined by the spacing between two adjacent stitch rows, and S_{Area} is the stitch thread cross-sectional area.

Resin XNR/H6813 was used to consolidate the composite by resin transfer molding technique. Specimens of 100 mm width and 150 mm length were then cut out from a mother plate using a diamond wheel cutter. The averaged plate thickness of the 20-ply specimen is 4.1 mm. The test specimens are produced by Toyota Industries Co. Ltd., All specimens are physically examined for any poor-resin regions and ultrasonic C-scanned for any delamination to ensure that they are free from any manufacturing related defects. Specimen notation used in this study is: for example, "400*d* 3 × 3" means stitch thread thickness of 400*d*, and stitch space and stitch pitch of both 3 mm. Examples of test specimens with different stitch density configurations are shown in Fig. 1. More details on the material preparation can be found in authors' earlier works [9,10].

2.2. Quasi-static indentation test

Quasi-static indentation (QSI) test was performed using Instron 5582 test machine (100 kN load cell) with a displacement control rate of 0.5 mm/min. The test specimen was placed on a support frame with a cut-out window of 76 mm by 127 mm and secured with four clamps with rubber tips along the sides, as depicted in