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Effect of stitch density on fatigue characteristics and damage mechanisms of stitched carbon/epoxy composites

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ABSTRACT

The effect of stitch density (*SD*) on fatigue life, stiffness degradation and fatigue damage mechanisms in carbon/epoxy (T800SC/XNRH6813) stitched using Vectran thread is presented in this paper. Moderately stitched composite ($SD = 0.028/\text{mm}^2$; 'stitched 6 × 6') and densely stitched composite ($SD = 0.111/\text{mm}^2$; 'stitched 3 × 3') are tested and compared with composite without stitch thread ($SD = 0.0$; 'unstitched'). The experiments show that the fatigue life of stitched 3 × 3 is moderately better than that of unstitched and stitched 6 × 6. Stitched 3 × 3 pattern is also able to postpone the stiffness degradation onset. The improvement of fatigue properties and postponement of stiffness degradation onset in stitched 3 × 3 is primarily due to an effective impediment of edge-delamination. Quantification of damage at various cycles and stress levels shows that stitch density primarily affects the growth rate of delamination.

1. Introduction

Laminated composites are susceptible to interlaminar damage widely known as delamination. Delamination reduces the integrity of composite, and causes some loss of its damage tolerance. A method to alleviate delamination is therefore desirable. Stitching is one of the effective methods to improve the delamination resistance in composites. It is done by inserting high-strength thread into composite in through-thickness direction. To avoid severe fiber breakage, stitching process is usually performed on the dry preforms rather than the uncured prepreg. When the stitched preforms have been made, they are subsequently infiltrated by the resin via resin transfer moulding or other processes. The resulting 'stitched composites' would contain a through-thickness reinforcement that may alter the mechanical properties and textile architecture of composites. The advantage of having stitches within composite systems is that they provide closure traction that reduces the tensile strain acting at the crack tip [1]. This interlaminar closure mechanism yields a considerable improvement of delamination resistance, and immediately translates into a better interlaminar fracture toughness and residual strength, e.g. compression-after-impact strength.

It should be firstly pointed out that stitching might be classified into two types: non-structural and structural stitching. Non-structural stitching is usually applied to provide a production ease or binding effect on the textile. In any textiles that are stitched using thin yarns (e.g. polyester with low linear density), the stitch thread does not add to the overall material properties, nor improve the damage tolerance. On the other hand, structural stitching is not only able to provide a binding effect or production ease on the textile, but it also changes the mechanical properties, architecture and the damage tolerance.

However, the main concern with structural stitching, as noted in Ref. [1], is that stitching induces architectural irregularities, such as fiber waviness, fiber breakage, fiber compaction, stitch debonding and resin-rich region. These irregularities, which are introduced during manufacturing process (thus they are called 'processing defects'), may act as a damage initiator or induce a rapid growth of damage. Another concern is that, for example, the effect of stitching on the in-plane mechanical properties as well as the damage mechanisms in composites under fatigue loading (a loading case of practical interest in the aircraft industry) is not known in details. Fatigue, which is characterized by the degradation of mechanical properties due to repeated, cyclic loading applied below the ultimate load, may result in a complete failure, or otherwise the degradation of stiffness. Although it was mentioned in Ref. [1] that

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the in-plane mechanical properties of stitched composites are generally lower than those of unstitched ones, however, the damage mechanisms related to various applied stresses for different type of stitch parameters have not been revealed. In fact, without understanding the basic properties and damage mechanism of stitched composites, specifically under fatigue loading, it may be difficult to undertake some actions to improve the architectural design of superior stitched composites. This may be a reason for the cautious use of stitched composites in the aircraft industry.

Reports on the fatigue of stitched composites have been published although the amount is limited. The findings have also been diverse to suggest a general conclusion on the efficacy of stitching in composites. Nevertheless, a general insight on fatigue properties of stitched composites can be reviewed in Refs. [1–4]. Following paragraph attempts to provide a brief literature review of the fatigue of structural and non-structural stitched composites.

The effect of structural stitching on fatigue properties has been reported earlier by Portanova et al. [5], who used thick S-2 glass fibers (3678 denier) to stitch AS4/3501-6. They found that stitching does not change the compression–compression open hole fatigue and failure mode of composite. The stitching only decelerated the progress of delamination without showing any other significant advantages. Vandermey et al. [6] reported the other investigation on fatigue of stitched composites. The material was the same as that in Ref. [5], which is AS4/3501-6 stitched using 3678 denier S-2 glass. They found that stitching induces some damage in composites, but at the same time, it is effective in reducing the delamination growth. An experimental study by Shah Khan and Mouritz [7] suggests that stitching significantly reduces tensile fatigue life of glass-reinforced polymer laminates when they are subjected to tension-zero load cycle (load ratio $R = 0$). The material was E-glass/vinyl-ester stitched using K40 Kevlar®. Stitch density was 0.03/mm^2 and 0.06/mm^2. Herszberg et al. [8] revealed that T300/epoxy stitched using Dyneema thread (148 denier) exhibits better fatigue performance than unstitched carbon/epoxy, or composite stitched using Kevlar (360 denier). Kevlar that has a larger diameter than Dyneema induced a more severe distortion on the carbon fibers. Aymerich et al. [9] reported that fatigue life of matrix-dominated AS4/3501-6 laminates of $[\pm 30/90]_S$ is improved with stitching (Kevlar, Ø0.25 mm), whilst that of fiber-dominated laminates of $[\pm 45/0/90]_S$ is reduced. Aymerich et al. [10] also found that fatigue life of stitched joints is improved up to five times when stitch pitch (distance between stitch penetration holes) of 2 mm is employed (stitch materials were Kevlar 198 denier and Dyneema 148 denier). Mouritz [11] found that fatigue performance of stitched E-glass/vinyl-ester is reduced by nearly one order of magnitude, i.e. ten times, although the content of Kevlar thread (360 denier) used was only 0.8%. Carvelli et al. [12] (who investigated carbon/epoxy NCF that is structurally stitched using carbon thread 600 denier) and Vallons et al. [13,14] concluded that fatigue life of stitched NCF is dependent on the direction of stitching. They found that if the direction of stitching is in-line with the direction of fatigue loading fatigue life of NCF is improved, vice versa. Beier et al. [15] found that the investigated stitch yarns (polyester 95 denier, polyamide 41 denier, polyamide 135 denier, phenoxy 270 denier) generally shortens fatigue life of carbon/epoxy NCF at high stresses. Fatigue strength and damage process caused by stitching in glass/polyester under fatigue loadings (tension–tension and compression–compression) was investigated by Aono and co-workers [16,17]. Under tension–tension loading (load ratio $R = 0.1$), the stitch content of 1.5–2% reduced fatigue strength of composites, while under tension–compression loading ($R = -1$) stitching is beneficial due to the suppression of delamination. Authors [18] also reported some reduction of fatigue life when circular stitching using Kevlar (1000 denier) is used for open hole specimens. When parallel stitching is used, the effect of Kevlar stitch on fatigue life is only apparent in compression–compression loading case, or above 8 million cycles in tension–tension case. A recent investigation on fatigue is reported for non-structural stitched composite. Adden and Horst [19] focused on the fatigue behavior of E-glass NCF laminates stitched using PES (poly-ether-sulfone) with mass per unit area of 12 g/m^2. Damage development (crack density in a tube specimen) was counted, and stiffness degradation due to fatigue loading in stitched NCF was numerically modeled. They found that the stiffness degradation and fatigue crack growth in stitched NCF is dependent on stitching direction.

Nonetheless, literatures of fatigue behavior of stitched composites spanning for more than two decades above indicate that the effect of stitch density on fatigue characteristics, which include stiffness degradation and damage development, of composite has not been studied in details. The quantification of damage in stitched composites that may reveal the damage mechanisms and the advantage of stitching is lacking.

The objective of this paper is therefore to investigate the effect of stitch density on carbon/epoxy composites in terms of fatigue life (S–N curves), stiffness degradation and fatigue damage growth. Static tensile test that reveals the effect of stitch density on tensile properties and corresponding damage mechanisms is also given based on authors' earlier findings [20]. Carbon fiber T800SC-24k are reinforced with Vectran® HT stitch thread (200 denier) in modified-lock stitch pattern, and infused with epoxy resin. Two types of stitch density are investigated: 0.028/mm^2 (moderately stitched composite) and 0.111/mm^2 (densely stitched composite). Fatigue damage in stitched composites is assessed by quantifying the growth of transverse crack, oblique crack and delamination with the aid of X-radiography technique.

2. Experimental details

2.1. Materials and test specimen

Material system used is carbon/epoxy composite reinforced using stitched thread. Carbon is T800SC-24kf (Toray Industries), epoxy is XNRH6813 Denatite (Nagase Chemtex) and stitch material is Vectran®HT (Kuraray) with linear density of 200 denier (22.2 tex). Material properties for T800 fiber, epoxy and Vectran can be reviewed in Table 1 [20]. Tow orientation is $[+45/90/-45/0_2/+45/90_2/-45/0]_S$, which is a 20-ply fabric preform.

Stitch type used to bind the dry preforms is modified-lock stitch consisting of needle and bobbin threads running parallel (x-direction) and perpendicular (y-direction), respectively, with respect to 0° plies. Fig. 1a shows the schematic of modified-lock stitch pattern in which the positioning and direction of needle and bobbin threads are indicated. Spacing in Fig. 1 denotes the distance between two needle thread lines, whilst pitch denotes the distance between two stitch penetration holes. Fig. 1b shows the top view of stitched composite showing +45° tows, resin-rich region and Vectran stitch threads. Fig. 1c shows the bobbin thread and stitch knot (a location whereby the needle thread binds the bobbin thread).

The manufacture of stitched composites was performed by Toyota Engineering Corporation using their specialized method, which follows these general steps: (1) arrangement of dry fabric preforms onto the metal frame surrounded by a number of pins, (2) simultaneous insertion of needle and bobbin threads into the preforms, (3) resin infiltration and curing processes. Epoxy was cured at the temperature of 120 °C for 2 h, and at 180 °C for 4 h. The resulting mother plate was approximately 310 mm long and 205 mm wide. The manufacturing process of unstitched composite plates is similar with that of stitched composites. However, tooling adjust-