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Compression properties and damage mechanisms of stitched carbon/epoxy composites

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ABSTRACT

The effect of stitching on compression properties and damage mechanisms of carbon/epoxy composites is experimentally investigated. The waviness angle of load-bearing tows is also measured in both in-plane and out-of-plane directions, and a correlation is made between compression strength and the waviness angle. It is found that stitching generally reduces the compression strength of carbon/epoxy composites of up to 16%. The average compression strength has a stronger correlation with the in-plane waviness angle rather than the out-of-plane one. A comparative damage assessment, which studies the initiation, progression and final failure in stitched and unstitched composites under axial compression, reveals that the early cracking in resin-rich region is responsible for the lower compression strength experienced by the stitched composites. The interaction between resin cracking and fiber splitting near the flank of wavy fibers accelerates the development of fiber kinking, and causes an early failure in stitched composites.

1. Introduction

The three-dimensional (3-D) composites have been a preferred choice over the two-dimensional (2-D) ones due to their excellent out-of-plane properties [1]. One of the 3-D composites that receive a great interest is stitched composites. Stitched composites, which can be fabricated by inserting high-strength threads in through-thickness direction into the preforms prior to resin consolidation process, exhibit superior impact resistance, compression-after-impact strength and interlaminar fracture toughness as compared to 2-D or unstitched composites [2]. However, in-plane mechanical properties of composites may be degraded with this kind of through-thickness reinforcement method.

A serious concern has particularly been given to the in-plane mechanical properties of stitched composites under axial compression because compressive strength, for instance, is fundamentally important in the aircraft design phases. The response of stitched composites under axial compression, particularly in cases whereby impact damages are absent, has been investigated by a number of researchers for almost 20 years. The investigation results, however, are markedly diverse in the sense that some researchers found that stitching does not alter compression properties of composites [3–6], whilst others found that stitching could improve the properties [7]. However, in most cases, the stitching reduces compression strength of up to 55% depending on the type of composite system, stitching parameters and fixtures [8–10]. The change in compression properties are often related to the following mechanisms: fiber kinking as a principal damage mode, and fiber waviness angle as a predominant factor [11–13].

Notwithstanding earlier investigations, no work has been done to describe the actual sequence of compression failure in stitched composites, and thence, a correlation between the failure mechanism and compressive strength has not been revealed. Stitch threads usually produce processing irregularities, such as fiber waviness and stitch debonding. The fiber waviness and its correlation with compression strength have not been systematically assessed for stitched composites, particularly with varying stitch density and thread thickness. Such correlation has actually been performed for other composite systems [14–17].

This paper presents an experimental investigation of mechanical behavior of carbon/epoxy composites stitched using Vectran® thread under axial compression. The composite system discussed herein is the same as that in Refs. [2,18,19]. This paper aims to understand the followings: (i) the effect of stitch density and thread thickness on the compression properties of carbon/epoxy, (ii) the correlation between compression properties and fiber waviness angle, (iii) the detailed damage mechanisms in unstitched and stitched composites under compression.

2. Experimental details

2.1. Materials

Carbon/epoxy composites were used in the investigation. Carbon was T800SC-24kf (Toray Industries) [20], while the epoxy was XNR6813/XNH6813 Denatite (Nagase ChemteX) [21]. Two

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composite systems were prepared: stitched and unstitched composites. The stitch material used for stitched composites was Vectran HT (Kuraray) [22].

The manufacture of stitched and unstitched composites was performed by Toyota Engineering Corporation using their specialized method derived from the one in Ref. [23]. In the manufacturing process, the fibers were initially arranged with tow orientation of $[+45/90/-45/0_2/+45/90_2/-45/0]_S$ to produce dry-fabric preforms. Stitch threads were then inserted into the preforms by adopting modified-lock stitch pattern (Fig. 1a), in which needle and bobbin threads are parallel with x-axis and y-axis, respectively. After carbon preforms were stitched, epoxy was then infused into the preforms by employing Resin Transfer Moulding (RTM). The composite was cured at 120 °C for 2 h and, subsequently, at 180 °C for 4 h. Nominal dimension of resulting composite plate was 310 mm long and 205 mm wide. The thickness of plate was approximately 4 mm. Fiber volume fraction achieved was between 52.6% and 54.4%. The terminologies used to describe stitched composites are stitch density (SD), pitch (p), spacing (s) and stitch volume fraction (V_s). Two stitch densities were predefined for stitched composites: 6 × 6 (s = 6 mm, p = 6 mm, SD = 0.028 mm^{-2}) and 3 × 3 (s = 3 mm, p = 3 mm, SD = 0.111 mm^{-2}). Two thread thicknesses were also used: 200 denier (200d) and 400 denier (400d). In total, five specimen types were prepared based on the stitch density and thread thickness: (i) unstitched (baseline, code: CN), (ii) stitched 6 × 6 200d (code: CS62), (iii) stitched 6 × 6 400d (code: CS64), (iv) stitched 3 × 3 200d (code: CS32), and (v) stitched 3 × 3 400d (code: CS34) (see Fig. 1b). Specimen codes, dimension, fiber volume fraction and other specifications are given in Table 1.

2.2. Compression test

The test specimen used in compression test was 80 mm long and 15 mm wide. The total length of clamping region at both ends was 70 mm, allowing a relatively small gauge area of 10 mm long and 15 mm wide. It was noted that only a limited number of stitches could be accommodated by the gauge area. In present case, the cutting of composite plate to produce test specimens was performed to achieve as many stitches as possible within the gauge area of 10 mm × 15 mm. For example, twenty-five stitches were penetrating the gauge area of stitched 3 × 3 specimens in z-direction. Of the stitched 6 × 6 specimens, there were six stitches allocated in the gauge area. The relatively small number of stitches in the stitched 6 × 6 should not be considered too few in terms of the architectural changes incurred, e.g. waviness, resin-rich region, since the damage in stitched composites under compression may initiate from one of the resin-rich regions or stitches.

The specimen was obtained by cutting the composite plate using water-cooled cutting machine AC-400CF (Maruto). The specimen edges were subsequently polished using abrasive sandpapers. Longitudinal and transverse strain gages (Kyowa, gage length = 2 mm, gage factor = 2.09 ± 1.0%) were attached on the front and back faces of the specimen, respectively. The fixture so-called NAL-II developed by Japan Aerospace Exploration Agency was used during the compression test [24]. NAL-II was selected because the experimental results obtained by this fixture were deemed reliable, repeatable and similar to those obtained by well-known standards of SRM-1 (SACMA) and ASTM D6641 (CLC) [25]. The compression test was carried out using universal testing machine Instron 4505 with maximum load-cell capacity of 100 kN. The loading rate applied was 1 mm/min. Environmental setting was set at room temperature of 20 °C. The load and displacement data were registered using Bluehill software. For each material type, at least five specimens were tested to obtain compression strength (σ_{uc}) and compression modulus (E_x). The procedures to conduct compression test, and to calculate the strength and the modulus can be reviewed in Ref. [26].

2.3. Measurement of fiber waviness

Fiber waviness in composites, or local deviation of fibers relative to their predetermined axis, is influenced by a number of

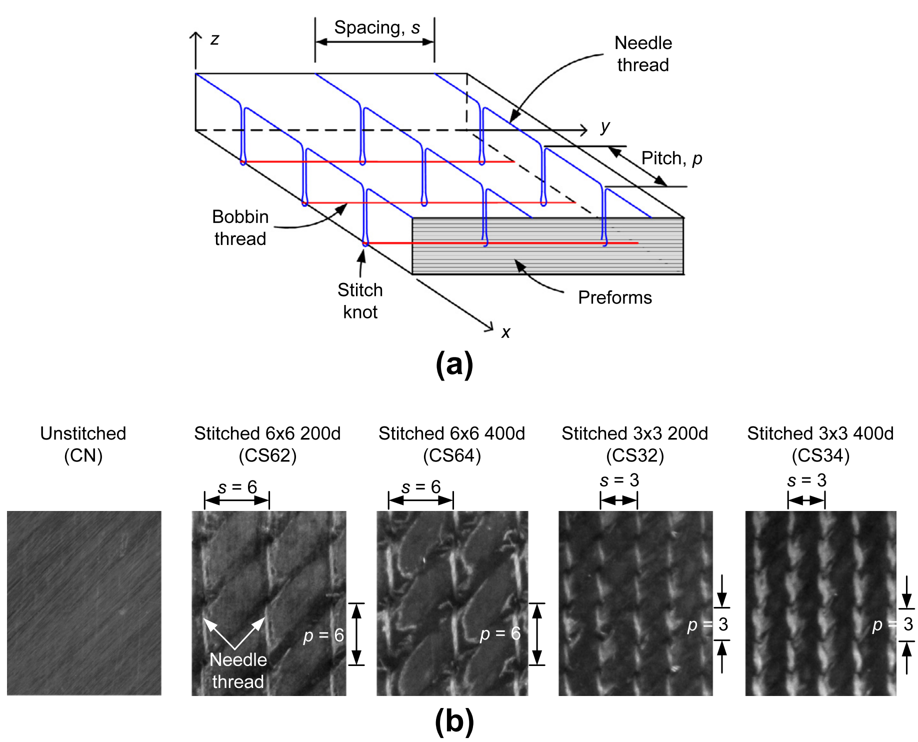

Fig. 1. (a) Modified-lock stitch pattern and terminologies used in stitching process, (b) five composite types under investigation: unstitched, stitched 6 × 6 200d, stitched 6 × 6 400d, stitched 3 × 3 200d, stitched 3 × 3 400d (dimension in mm).