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Investigation into the tensile properties of ISO-401 double-thread chain-stitched glass-fibre composites

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ABSTRACT

Interlaminar stitching has proven to be an effective through-thickness reinforcement technique for laminated composites but a major drawback is the negative effect it has on the in-plane tensile properties. This study aims to optimise stitching for composites to reduce the associated negative effects by introducing a new stitch type to composite laminates. The double-thread chain-stitch (ISO-401) has shown great utility in the textile industry but has not yet been applied as through-thickness reinforcement to composites. In this paper, tensile properties of glass fibre composite laminates stitched with ISO-401 double-thread chain stitch have been examined, as stitching reduces in-plane strength while improving damage tolerance. Three variations of the ISO-401 geometry were employed by varying the stitch junction position and each position was applied at two stitch densities by varying the stitch pitch at 3 mm and 4 mm. The composites were manufactured using E-glass 2 × 2 twill fabric and a Bisphenol-A type epoxy resin, stitching was performed with core-spun tex 24 polyester thread. The experimental data demonstrated the influence of ISO-401 junction position and stitch density on the composite tensile properties. Furthermore, adjustment of the junction position was found to affect the size of stitch-induced resin pockets and severity of in-plane fibre misalignment.

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1. Introduction

Fibre reinforced polymer (FRP) composites are used extensively throughout the aerospace industry, increasingly in the manufacture of structural parts, due to their high specific strength and stiffness, good corrosion and fatigue performance, compared with their metallic counterparts [1,2]. Two-dimensional (2D) laminated composites offering excellent in-plane mechanical properties are used increasingly in these structures but a critical limitation is their low resistance to out-of-plane loading and susceptibility to delamination, which are situations that may arise from geometrical defects, manufacturing defects, or low-velocity impact [3–5].

Improving the out-of-plane resistance to delamination in composites is achievable through techniques such as, stitching, pinning, tufting and three-dimensional (3D) weaving. Extensive work has reported stitching as an effective, low cost option of through-thickness (TT) reinforcement to improve the interlaminar fracture toughness (IFT) and impact resistance of composites [4,6–11]. There is a growing interest in TT stitching as it has been found to cause less in-plane damage compared to z-pinning and to degrade, or less commonly, improve, the tensile properties by up to 20% which is comparable to the properties of 3D woven structures [12,13]. Moreover, stitching is an attractive option for the reinforcement of structural composites because existing textile technologies and techniques can be used.

An extensive range of stitch parameters, such as: stitch geometry, stitch density, needle type, stitch thread linear density, stitch thread type, stitch thread tension, machine feed type, presser foot force and speed can be varied to tailor the design of the final composite. While it is difficult to consider the effect of all these parameters, stitch density and stitch thread linear density have been found to improve the delamination resistance of laminated composites. For example, quasi-static indentation loading of carbon fibre Vectran stitched composites revealed that increasing stitch density significantly reduced damage propagation because closely
spaced stitches were able to bridge delamination cracking and arrest crack propagation [14]. It was also found that increasing stitch density and linear thread density improved the mode I IFT [9,10] and compression after impact strength of stitched composites [15].

However, a major concern for TT stitching is the impact it has on the composite in-plane tensile properties. Although interlaminar stitching shows great promise as an out-of-plane reinforcement technique, the effect of TT stitching on the in-plane tensile properties is concerning and less-well understood. The stitching process causes microstructural defects including in-plane fibre distortions, fibre breakages, and resin pockets, which negatively affect the tensile properties [1,12,16–19]. Resin pockets are considered structural weak points due to the reduction of fibre reinforcement in these regions and under loading conditions, cracks propagate from these areas due to stress concentration [20]. Fibre reinforced composites, due to their anisotropic nature, exhibit highly complex damage mechanisms the resulting failure modes are also complex [21,22]. Researchers have reported new and different dominating damage mechanisms in stitched composite specimens compared with unstitched counterparts [19,23]. The changes in damage modes are associated with the microstructural changes and damage imparted by the stitching process to the final composite geometry.

From the limited research that is available, it is frequently the case that TT stitching causes a reduction in tensile properties [12]. For example, researchers have found that as stitch density increases, the tensile properties are reduced [1,23–26]. This is considered a major drawback to the use of TT stitched FRP composites as tensile properties, in particular tensile modulus, are critically important to engineering applications. Therefore, working to reduce the negative effect that stitching can have on the tensile properties of FRP composites is important during their design and manufacture. Ultimately, for TT stitched composites, the in-plane properties should, at the very least, be maintained whilst out-of-plane properties must be significantly improved [1].

Considering the negative impact that stitching has on the FRP composite structure and the tensile properties, some work has been done to modify the common textile lockstitch (ISO-301) for composite reinforcement. It is understood that the stitch geometry affects the final composite properties because the stitch formation path is different depending on the stitch type [27]. ISO-301 is the most common type of stitch geometry used in the textile industry and subsequently, a lot of interest has been focused on using ISO-301 in composites [12]. For TT stitching, the original ISO-301 geometry has been modified by researchers to reduce damage and stress concentration to FRP composites by ensuring the interlacement between the needle and bobbin thread occurs on the surface of the plies, rather than in-between plies as in standard ISO-301 stitching [3,8]. This results in the bobbin thread acting as the z-direction reinforcement, an advanced thread such as glass or carbon fibre is usually employed. Fig. 1 provides schematics of the lockstitch geometries. However, there are some major challenges associated with the production of ISO-301 composites; (i) modified ISO-301 composites still suffer from resin pockets and other structural defects [3,12], (ii) the rotary hook mechanism can damage brittle advanced fibres as they are unwound from the bobbin case, (iii) the bobbin supply for an industrial machine holds a very small volume of thread compared to the needle thread creel, this results in the repetitive pausing of manufacturing to remove the empty bobbin cases and replace the thread.

This work investigates the potential of a new stitch type for TT composite reinforcement, the double thread chain-stitch (ISO-401). This new stitch type presents the opportunity to further optimise stitching for composites and reduce the negative impact that stitching has on FRP composite tensile properties. To create the ISO-401, two threads are employed, an upper needle thread and a lower looper thread. The resultant geometry is such that the needle thread acts as the reinforcement thread being interlaced in the TT direction and the looper thread is essentially a holding thread, a schematic of the geometry is presented in Fig. 1. The ISO-401 is a common stitch type for the textile industry and it is anticipated to address some of the issues associated with ISO-301 TT stitching. A major advantage is that the inter-looping junction between the needle and looper thread can occur internally to the needle hole or externally, between adjacent needle holes, via adjustment of the thread tension wheels or the relative timings between the take-up mechanisms and the feed system. It is anticipated that the flexibility in inter-looping positioning during stitch formation would allow for the geometry to be optimised for composites to reduce in-plane fibre distortion. There are also manufacturing related advantages associated with the use ISO-401; firstly, the action of needle thread insertion is less damaging to advanced brittle fibres compared with ISO-301 stitching and secondly, both needle and looper threads are supplied on industrial size creels. Therefore, thread replacement occurs more infrequently compared with ISO-301 production.

It is clear that TT stitching nearly always causes degradation in tensile properties, therefore in order to contribute to the optimisation of TT stitching for composite reinforcement, this paper considers the effect of the novel ISO-401 needle and looper thread inter-looping junction position on the tensile properties of glass fibre reinforced polymer (GFRP) composites. The effect of different stitch junction positions is also investigated in two different stitch densities.

2. Materials and methods

2.1. Composite manufacturing

The experiments in this paper were performed on unstitched and stitched composites made from eight layers of E-glass 2 × 2 twill woven fabric with a mass of 280 g/m² (supplied by Easy-Composites Ltd). The filament diameter was 13 μm and the warp and weft densities were 8 × 7 cm. Two types of composites were manufactured, unstitched (UNS) and ISO-401 machine-stitched (A, B and C) preforms. Stitching was conducted on the dry preforms,

Fig. 1. Stitching geometry schematics; (a) ISO-401 with internal junction; (b) ISO-401 with external junction; (c) Standard ISO-301; (d) modified ISO-301.
prior to the vacuum assisted resin infusion moulding (VARIM) process, the stitching process is discussed in detail in Section 2.2. The preforms were consolidated with a Bisphenol-A type epoxy (Araldite LY1564) resin and an amine type (Aradur 2954 cycloaliphatic polyamine) hardener (supplied by Huntsman UK Ltd). The resin system was mixed homogeneously then applied to the preform at 20 °C using VARIM technique as in [28]. The curing conditions were 2 h at 80 °C followed by 8 h at 140 °C and composite plate dimensions were 300 mm × 300 mm × 1.7 mm. Theoretical fibre volume fraction ($V_f$) was calculated using the following equation:

$$V_f = \frac{nA_f}{\rho_f t_c}$$  \hspace{1cm} (1)

where $n$ is the number of plies, $A_f$ is the areal weight of the fabric, $\rho_f$ is the fibre density, and $t_c$ is the thickness of the composite laminate.

2.2. TT stitching process

Stitching was performed on the preforms using an industrial ISO-401 double-thread chain-stitch Durkopp Adler 195-171120-01 machine. Fig. 2 displays an image of the in-situ stitching of a glass fibre preform. The sewing thread used was polyester core-spun with a thread density of 24 tex (supplied by Coats Ltd). There were three sub-groups of the machine stitched composites, each with a different placement of the interloping junction. Composite type A had an external junction position, type B had an external-central junction position and type C had an internal junction position, schematics of junction positions are presented in Fig. 2. The inter-looping position of the threads was adjusted by increasing or reducing the needle thread ($T_n$) and looper thread ($T_l$) tensions via the corresponding tension wheels, thus each of the three junction positions had different overall stitch tension ($S_T$) values. Specification of the composite properties can be viewed in Table 1. For all stitched specimens, ISO-401 stitching was conducted in the 0° direction and was applied in two different densities by varying the stitch pitch ($S_p$) at 4 mm and 3 mm, the stitch space ($S_s$) was maintained at 10 mm. Stitch density ($S_D$) was calculated using the following equation, as in [14]:

$$S_D = \frac{1}{S_p \times S_s}$$  \hspace{1cm} (2)

where $S_p$ is defined as the distance between two adjacent stitch holes and $S_s$ is the distance between two parallel stitch rows. A schematic of stitch arrangement can be viewed in Fig. 2.

To determine $V_f$ of the stitched composites, the value of stitch thread consumption was required. There are different methods for calculating thread consumption for ISO-401 recorded in the literature but few of them consider the effect of stitch tension along with fabric thickness, stitch density and thread linear density [29]. It was important to consider the effect of stitch tension on thread consumption as the stitch tension varied for the different stitch junction positions developed in this work. Considering this, thread consumption was defined per 10 cm stitching length for needle thread ($D_n$) using Eq. (3) and looper thread ($D_l$) using Eq. (4), as in [29]:

$$D_n = 0.25nT + 4.137c + 4.836eT - 4.154T + 61.027$$  \hspace{1cm} (3)

$$D_l = 2.312n + 2.623c + 2.53T + 351.32$$  \hspace{1cm} (4)

where, $n$ is stitch density (stitches per inch), $c$ is the linear density in tex of the sewing thread, $T$ is the corresponding thread tension and $e$ is the fabric preform thickness. For stitched composites, the

Fig. 2. Stitch junction schematics of (a) type A external; (b) type B external-central; (c) type C internal; (d) image of preform ISO-401 stitching; (e) schematic of stitch space ($S_s$) and stitch pitch ($S_p$) for calculation of stitch density ($S_D$).
3.1. Tensile results

Tensile testing was conducted to investigate the mechanical properties of the stitched and unstitched composites, namely tensile strength ($\sigma_{UT}$) and tensile modulus ($E_t$). The testing was carried out in-line with the industry standard ASTM D3039M on a commercial INSTRON-5569 machine in ambient conditions [30]. The tensile test was repeated 3 times for each composite type due to limited test specimens. The test parameters recommended by the standard were as follows: 50 kN load cell, 2 mm/min cross-head speed, using an extensometer with 200 mm (length) and a gauge length of 25 mm (width) x 250 mm (length) and a gauge length of 150 mm $E_t$ was defined according to the standard as the slope between $\epsilon = 0.1\%$ and $\epsilon = 0.3\%$. Loading was applied in the 0° direction, which was the same as the stitching direction. Following tensile testing, an optical microscope was used as an imaging technique to examine the specimen surfaces and identify the damage caused by interlaminar stitching for all stitch types studied. Resin pocket void areas in the cross section of A-4, B-4, and C-4 were quantified from the micrographs.

3. Results and discussion

3.1. Tensile results

The fibre volume fraction results and tensile properties for all stitched and unstitched composites are presented in Tables 1 and 2. Representative stress strain curves are presented in Fig. 3A. Fibre volume fraction was not significantly affected by the presence of the stitching thread in the TT stitched composites. This is likely because the stitching thread used was very fine.

The tensile strength for UNS, A-4, A-3, B-4, B-3, C-4, and C-3 were 349 MPa, 362 MPa, 310 MPa, 355 MPa, 282 MPa, 363 MPa, and 352 MPa respectively. Comparison of tensile strength for unstitched and stitched composites is presented in Table 2. The tensile strength of UNS and stitched specimens with 4 mm stitch pitch are similar and in the case of A-4 and C-4 slightly improved, though the improvement did not reach statistical significance at a threshold of $p < 0.05$. However, when the stitch pitch was reduced (3 mm) to increase the stitch density, the tensile strength was significantly reduced in A-3 and B-3 composites by 11% and 19% respectively, compared to UNS composites. For C-3, tensile strength value was maintained.

The values of tensile strain for UNS, A-4, A-3, B-4, B-3, C-4, and C-3 were 2.3%, 2.2%, 2.2%, 2.2%, 2.3%, and 2.4% respectively. For all of the stitched specimens, the tensile strain was maintained or slightly improved when a moderate stitch density ($S_p = 4\, \text{mm}$) was employed. When dense stitching was employed ($S_p = 3\, \text{mm}$), for C-3 type composites tensile strain was unaffected but in the case of A-3 and B-3 composites, it was reduced slightly. A comparison of tensile strain values for stitched and unstitched specimens is presented in Table 2.

3.2. Tensile failure

Fig. 3C shows the tensile failure sites for stitched and unstitched specimens. Tensile failure occurred perpendicular to the load direction in the gauge length for both UNS and DCS composites. For UNS specimens, post-mortem investigation revealed the dissipation of energy in the form of fibre pull-out, fibre fracture, matrix fracture, and extensive delamination at tensile failure site. For stitched specimens damage mechanisms observed were: stitch thread breakage, fibre pull-out, matrix cracking, and local delamination. For A, B, and C type composites, stitching was found to maintain the specimen integrity and reduce the delamination area at the tensile failure site, compared to UNS specimens. The damage initiation was audible in stitched specimens at around 40% of ultimate tensile strength, compared to 60% for the UNS specimens.

Table 1
Specification of stitched and unstitched composite specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Junction type</th>
<th>$t_i$ [mm]</th>
<th>$V_f$ [%]</th>
<th>$S_p$ [mm]</th>
<th>$S_d$ [mm]</th>
<th>$S_{g} [\text{mm}^{-2}]$</th>
<th>$T_n$ [gf]</th>
<th>$T_f$ [gf]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNS</td>
<td>N/A</td>
<td>1.70</td>
<td>51.9</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>A-4</td>
<td>External</td>
<td>1.74</td>
<td>51.2</td>
<td>4</td>
<td>10</td>
<td>0.025</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>A-3</td>
<td>External</td>
<td>1.74</td>
<td>51.1</td>
<td>3</td>
<td>10</td>
<td>0.033</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>B-4</td>
<td>External-central</td>
<td>1.73</td>
<td>51.6</td>
<td>4</td>
<td>10</td>
<td>0.025</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td>B-3</td>
<td>External-central</td>
<td>1.74</td>
<td>51.5</td>
<td>3</td>
<td>10</td>
<td>0.033</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td>C-4</td>
<td>Internal</td>
<td>1.72</td>
<td>52.0</td>
<td>4</td>
<td>10</td>
<td>0.025</td>
<td>70</td>
<td>180</td>
</tr>
<tr>
<td>C-3</td>
<td>Internal</td>
<td>1.72</td>
<td>51.8</td>
<td>3</td>
<td>10</td>
<td>0.033</td>
<td>70</td>
<td>180</td>
</tr>
</tbody>
</table>

Table 2
Longitudinal tensile properties of stitched and unstitched composites, standard deviation is shown in brackets.

<table>
<thead>
<tr>
<th>Properties</th>
<th>UNS</th>
<th>A-4</th>
<th>A-3</th>
<th>B-4</th>
<th>B-3</th>
<th>C-4</th>
<th>C-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{UT}$ [MPa]</td>
<td>348.9 (9.6)</td>
<td>361.6 (10.1)</td>
<td>310.1 (6.0)</td>
<td>355.3 (5.3)</td>
<td>281.7 (7.4)</td>
<td>364.3 (6.5)</td>
<td>352.4 (9.0)</td>
</tr>
<tr>
<td>$\epsilon_f$ [%]</td>
<td>2.32 (0.04)</td>
<td>2.34 (0.08)</td>
<td>2.21 (0.03)</td>
<td>2.35 (0.11)</td>
<td>2.19 (0.08)</td>
<td>2.31 (0.24)</td>
<td>2.35 (0.22)</td>
</tr>
<tr>
<td>$E_t$ [GPa]</td>
<td>16.9 (0.3)</td>
<td>17.2 (0.2)</td>
<td>15.0 (0.6)</td>
<td>17.3 (0.4)</td>
<td>16.5 (0.5)</td>
<td>17.0 (0.4)</td>
<td>16.9 (0.8)</td>
</tr>
</tbody>
</table>
This suggests that the resin pockets in stitched composites acted as stress concentrators and crack initiation sites during tensile loading.

3.3. Distortion of in-plane fibres

It is clear from the optical microscopy analysis conducted for this paper that stitching with DCS geometry introduces structural deformations to the final GFRP composite. Optical images of in-plane fibre distortion and subsequent resin pockets around the stitching holes in the final structures for all stitched specimens were confirmed, as expected. Example images of fibre deviations in preforms and resin pockets in the composite cross-sections can be seen in Fig. 3D. For A-4, B-4, and C-4 type composites, the average measurements for resin pocket areas in the composite cross-sections were 50.0, 56.4 and 20.0 μm² respectively, a comparison of resin pocket areas for stitched composites is presented in Fig. 3D.

These structural defects are common stitched-related damage types that have been identified in FRP composites stitched with modified lockstitch [1,12,26] and are predicted to occur with the insertion of any two-thread stitch geometry. In-plane fibre deviations occur initially due to the needle penetration moment pushing apart the 0° and 90° directional fibres. Once the needle is removed, the needle thread is left behind in the structure causing in-plane fibres to remain deformed around the thread, commonly referred to as fibre waviness. During infusion, these structural voids are filled with resin and act as stress concentration and crack initiation sites.

4. Discussion

For each of the stitch junction types when a 4 mm stitch pitch was employed, the properties of tensile strength, strain and modulus were mostly maintained and in some cases slightly improved. A combination of fine stitching thread and optimum stitch distance has likely caused less structural damage to the composite and resultant stress concentration in these cases, compared to higher density stitching. This is in line with the literature, as very high or low densities are considered to cause stress concentration during tensile loading. On the other hand, optimum densities and stitch conditions have been found to contribute to even distribution of load transfer [20]. Therefore, from the results, the ISO-401 geometry with stitch pitch at 4 mm is considered to show the best compatibility as TT composite stitch type. However, high density TT stitching has been shown to improve the interlaminar properties more effectively [7,9,10] and therefore examining the tensile properties of the three ISO-401 junction types with suitably high stitch density was a key aspect of this research.

Once the stitch density was increased, a reduction in tensile properties was evident for A and B junction positions, whilst it was
maintained for C type composites. A common feature of both type A and B composites is that the inter-looping junction of the needle and looper threads occurred at a position between the two needle points. In the case of B type composites, where the junction position occurred just outside of the needle hole, when the stitch density was increased ($S_p = 3\, \text{mm}$), the tensile properties were reduced in comparison with B-4 composites and UNS counterparts. Compared with B-4 composites, the tensile strength, strain and modulus properties were reduced by 21%, 7% and 5% respectively, and by 19%, 6% and 2% respectively compared with UNS composites. When the position of the junction was at the furthest point from the needle hole, as in A type composites, when the stitch density was increased the tensile strength, strain and modulus properties were reduced by 14%, 6% and 13% respectively, compared with A-4 composites, and by 11%, 5% and 11% respectively compared with UNS composites. It is suggested that the junction positions of A-3 and B-3 type composites caused significant structural deformation and damage to the composite structures, in the form of fibre waviness and resin pockets which resulted in reduced tensile performance when the stitch density was increased.

It is well established that the distortion (waviness) of in-plane fibres results in resin pockets in the final composite structure. Fibre waviness occurs around the needle thread insertion point as the in-plane fibres are deviated from their intended path to accommodate the needle action and inserted needle thread. Fibre waviness is predicted to affect the tensile properties, for example, researchers have found a strong correlation between waviness angles of $0^\circ$ fibres and tensile modulus [1]. The tensile modulus decreased as the waviness angle increased due to off-axis loading effects. Whilst resin pockets are expected to be found in composites stitched with two threads, attempting to minimise them and their detrimental effect was one important aspect of this work. For A and B type composites, where the inter-looping position occurred towards the middle of two needle points, the distance between the insertion needle thread and the return needle thread was wider, thus distorting in-plane fibres more significantly along its path. This is evident as resin pockets in type A and B composites were 60% and 65% larger in comparison to those measured in type C composites. Therefore, the reason for A-3 and B-3 composites having significantly reduced tensile properties is predicted to be a combination of both the size and frequency of resin pockets and the associated structural distortions. Firstly, it is expected that type A and B composites suffered from high amounts of in-plane fibre distortion (waviness), compared to type C composites, due to the larger resin pockets identified in their structure. These effects were more pronounced when the stitch density was increased (A-3 and B-3) because the total number of resin pockets increased. Therefore, a higher degree of fibre waviness for type A-3 and B-3 composites caused more lateral deformation to occur during loading and resulted in reduced tensile properties.

In C-3 composites, the tensile strength, strain and modulus properties remained similar to that of C-4 and UNS composites. This suggests that the specific stitch geometry employed in C type composites had a minimal negative effect on the in-plane fibres hence preserving the tensile properties, even when the stitch density was increased (C-3 composites). For this stitch geometry, the needle thread path did not extend along the surface of the composite as in junction types A and B. Restricting the needle thread path so that the inter-looping junction occurred close to the needle hole resulted in a smaller distance between the insertion thread and returning thread. Resin pockets in the composite structure were also significantly smaller for C type composites compared with A and B type composites (60–65%).

Although further investigation into the structural deformations of ISO-401 stitched composites is recommended, this work suggests that using ISO-401 geometry with an internal stitch junction type for TT stitching of composites could provide comparable tensile properties with unstitched composites. It was found that C type iteration of the stitch geometry caused less damage to in-plane fibres and therefore the in-plane composite properties were mostly maintained. In this paper, reduction in tensile properties of TT stitched compared with unstitched composites never exceeded 19%, which is comparable to literature, as stitching with modified ISO-301 has been found to reduce tensile properties by up to 20% [12,13]. It is recognised that the employment of a TT stitching technique should provide excellent interlaminar performance combined with at least maintaining the in-plane tensile properties [1], therefore, investigating the interlaminar performances of ISO-401 composites is the next stage of this on-going research.

5. Concluding remarks

It is well documented that interlaminar stitching can improve the out-of-plane properties of composite laminates [4,6–10]. However, a major drawback to TT stitching is the negative impact it can have on the in-plane tensile properties of FRP composites [1,3,12]. The objective of this study was to attempt to optimise TT stitching using a new stitch type, ISO-401, in order to reduce some of the in-plane damage caused by stitching. This type of stitching is interesting for composites because the stitch geometry can be altered by changing the position of the point where the needle thread and looper thread inter-loop at the composite surface. Using the ISO-401 stitch type, stitched and unstitched composite equivalents for comparison were developed and were subjected to axial tensile loading. This paper was concerned with two aspects of ISO-401 stitched composites, firstly to investigate the effects of thread inter-looping position and secondly, to investigate the effect of two stitching densities on the tensile properties of GFRP composites. It can be concluded that stitch type ISO-401 showed good compatibility with GFRP composites and from the experimental results the following observations can be made: (i) changing the positioning of the needle thread and looper thread junction affects the tensile properties of GFRP composites, particularly when stitch density is increased; (ii) stitch junction position affects the average cross-sectional areas of resin pockets in the stitched composite structures; (iii) increasing stitch density does not reduce the tensile properties when junction occurs closer to needle hole and; (iv) any reductions in tensile properties caused by ISO-401 TT stitching did not exceed 19% which is in-line with the subject literature. Future work concerns experimentally investigating the interlaminar properties of ISO-401 composites with different stitch junction positions.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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