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Enhancing Mechanical Performance of Kevlar Composites Through Optimised Stitching Parameters

Izboljšanje mehanskih lastnosti Kevlarjevih kompozitov z optimiziranimi parametri šivanja

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Abstract

The study explores the development of stitched reinforced composites using Kevlar woven fabric as the primary reinforcement. The influence of stitching parameters, stitch type, needle type and stitches per cm (SPC) on the mechanical performance of the composites was systematically investigated. Kevlar fabric was stitched using different needle types and SPC values before being mechanically tested for tensile strength, delamination resistance and impact performance. The results demonstrate that composites stitched with a ballpoint needle using a chain stitch at 3.94 SPC exhibited the highest mechanical strength, with tensile strength increasing from 145 MPa (unstitched) to 191.5 MPa (lock stitch) and 240 MPa (chain stitch). Impact resistance improved from 98 kJ/m² (unstitched) to 133 kJ/m² (ballpoint needle, lock stitch), with chain-stitched composites showing even better performance due to the greater load distribution of the sewing thread and reduced fabric damage. Conversely, lock-stitched composites provided superior delamination resistance due to enhanced interlayer gripping. These findings highlight the potential of the developed composite for advanced protective applications, including bulletproof vests and aerospace structures requiring superior impact resistance and structural integrity.

Keywords: woven fabric, composites, stitching parameters, mechanical properties

Izvleček

Prispevek obravnava razvoj s šivanjem ojačanih kompozitov, pri katerih je kot primarna ojačitev uporabljena tkanina iz Kevlarja. Sistematično je bil preučen vpliv parametrov šivanja, vrste vboda, vrste igle ter število vbodov na centimeter (SPC) na mehanske lastnosti kompozitov. Kevlar tkanina je bila šivana z različnimi vrstami igel in SPC vrednostmi, preden je bila mehansko testirana na natezno trdnost, odpornost proti razslojevanju in odpornost proti udarnim obremenitvam. Rezultati kažejo, da so kompoziti, šivani z iglo z okroglo konico in verižnim vbodom pri 3,94 SPC, pokazali najvišjo mehansko trdnost; natezna trdnost se je povečala s 145 MPa

(nešivani) na 191,5 MPa (prešivni vbod) in 240 MPa (verižni vbod). Odpornost proti udarcem se je izboljšala z 98 kJ/m² (nešivan) na 133 kJ/m² (igla z okroglo konico, prešivni vbod), pri čemer so kompoziti z verižnim vbodom dosegli še boljše lastnosti zaradi porazdelitve obremenitve preko šivalne niti in manjše poškodbe tkanine. Nasprotno pa so kompoziti s prešivnim vbodom zagotavljali boljšo odpornost proti razslojevanju zaradi izboljšane oprijemljivosti med plastmi. Izsledki raziskave poudarjajo potencial razvitega kompozita za napredne zaščitne aplikacije, vključno z neprebojnimi jopiči in letalskimi strukturami, ki zahtevajo visoko odpornost proti udarcem in strukturno celovitost.
Ključne besede: tkanina, kompoziti, parametri šivanja, mehanske lastnosti

1 Introduction

Composite materials are characterised by multiphase materials within which the phase distribution and geometry have been deliberately tailored to optimise one or more properties [1, 2]. In this context, textile-reinforced composites have been widely used in design applications for many years, particularly in cost-effective solutions [3]. Composite materials consist of two primary components, i.e. reinforcement and matrix. The reinforcement, which provides strength and load-bearing capacity, can be made of glass fibres or other high-performance materials. The matrix, typically a polyester, epoxy or other resin, acts as a binding medium, transferring stress between the reinforcing fibres and maintaining the composite's structural integrity. Fibrous structures serve as the primary reinforcement, bearing the applied stresses and significantly influencing the composite's mechanical properties [4]. Commonly used reinforcements are glass fibre [5], carbon fibre [6] and Kevlar [7]. Reinforcement of fibre orientation and dimension decide the properties of composites. The lengthwise direction of fibres gives more mechanical properties than the widthwise direction, the resin being a chemical or polymer that behaves as a matrix for binding the fibrous reinforcement or works as an adhesive [8].

The resin component in composites can be thermoset (e.g. epoxy, polyester, vinyl ester) or thermoplastic (e.g. Polyether ether ketone, polypropylene, polycarbonate), with thermosets offering high thermal stability and adhesion, while thermoplastics provide recyclability, flexibility and impact resistance, making resin selection crucial for composite performance [9]. Fibre-reinforced polymer (FRP) composites have gained considerable attention for their high strength-to-weight ratio and superior durability. Among these, aramid-based composites, especially those using Kevlar, are extensively used in the defence, automotive and aerospace sectors. Stitching is a known method for enhancing interlaminar properties in composites. However, the effect of stitch parameters on the damage mechanisms and overall performance has not been studied systematically. Polyether ether ketone (PEEK), a high-performance thermoplastic polymer known for its excellent mechanical properties and chemical resistance, is often used in fibre-reinforced composites due to its compatibility with high-strength fibres like aramid. This study aims to fill this gap by investigating the influence of stitch type and needle geometry on the mechanical performance of Kevlar/epoxy laminates [10].

Aramid fibres, particularly Kevlar, are known for their exceptional mechanical performance, including high tensile strength, low density, excellent thermal stability, and resistance to impact and abrasion. These characteristics make aramid an ideal candidate for use in aerospace, ballistic and high-performance structural applications where durability and strength-to-weight ratio are critical [11]. Up until the 1900s, a lot of work was performed on natural fibres reinforced composites. Kevlar aramid (PPTA; poly (p-phenylene terephthalamide) fibre is broadly utilised as a part of the making of advanced composites [12].

Woven fabrics are the most widely used textile reinforcement in composite materials, offering versatility across various applications, including aerospace, automotive and protective gear. Their structured interlacing of warp and weft yarns ensures high dimensional stability and uniform mechanical properties. The development of carbon and aramid fibre fabrics, with superior stiffness compared to glass fibres, has further expanded the applicability of woven reinforcements. These fabrics exhibit excellent drapes, enabling the formation of complex shapes without gaps [13]. Additionally, woven fabric composites demonstrate enhanced impact resistance compared to nonwoven composites, significantly improving compressive strength after impact and making them ideal for high-performance applications [14].

Sewing the reinforcement is an effective method to enhance the through-thickness strength of composites, significantly improving their compression after impact (CAI) performance. This technique introduces mechanical interlocking between plies, which helps redistribute stresses and delay the initiation and propagation of delamination under impact or compressive loading. Failure in laminated composites is often initiated by micro-scale interfacial separations between layers, leading to progressive delamination and reduction in structural integrity. By stitching or sewing the reinforcement, resin-rich zones are locally modified, providing additional crack-bridging and load transfer pathways that enhance damage tolerance and energy absorption. Moreover, this method has been shown to improve post-impact stiffness and residual strength, making it particularly valuable for applications in aerospace, automotive and defence structures where lightweight yet damage-tolerant composites are critical. Recent studies have demonstrated that the choice of stitching pattern, needle type and thread material can further influence the mechanical performance and failure modes, enabling tailored reinforcement strategies for specific loading conditions. Overall, sewn reinforcements provide a practical and scalable approach to mitigating delamination-driven failures, offering significant improvements in both mechanical performance and structural reliability of composite laminates [15]. Yuan et al. investigated stitched composites with varying stitch densities to enhance their mechanical properties [16]. Previous research has primarily focused on improving the mechanical performance of composites through stitching; however, often without a detailed classification based on stitch class or needle geometry. For instance, Loi G. et al. [17] studied stitched laminates without detailing stitch patterns, while recent advancements in composite stitching techniques underscore the need for parametric optimisation to enhance strength and durability [18]. Plain and chain stitches were incorporated to reinforce the laminates along the z-axis, improving their through-thickness strength. The results showed that stitched composites exhibited an approximately 10% improvement in ballistic efficiency compared to conventional woven laminate composites, with the optimal stitch design playing a key role in this enhancement [19]. The following section outlines the materials and experimental methods used to fabricate and test the stitched Kevlar/epoxy composites, providing a foundation for evaluating how stitch class, stitch density and needle type influence performance. Bhavani V. Sankar et al. investigated the effects of stitching on the low-velocity impact response of stitched and delaminated beams, analysing their static and impact behaviour. A static contact force model was developed, and simulations identified displacement/crack extension and load/displacement relationships. Impact simulations provided insights into the load at crack initiation, peak contact force, and the extent of crack propagation at the end of impact. The study revealed that while stitching did not increase the load required for delamination initiation, it significantly reduced the extent of delamination, thereby improving the composite's damage tolerance [20]. Lopresto et al. investigated the effectiveness of stitching in enhancing the damage resistance of polymer composites against ballistic projectiles and explosive blasts. The study found that stitching reduced delamination damage caused by ballistic impact to some extent, while significantly improving damage resistance under explosive blast loading. This improvement was attributed to the increased interlaminar fracture toughness resulting from stitching. Additionally, stitched composites exhibited less overall damage and retained strength and flexural modulus comparable to unstitched composites after ballistic impact testing, highlighting their potential for high-performance protective applications [21]. Unlike prior studies that generally explored stitching effects without categorising based on needle geometry or stitch structure, this research distinctly evaluates the combined effects of stitch class (chain vs. lock) and needle type (sharp vs. ballpoint) on mechanical properties. This multidimensional optimisation has not been previously addressed in Kevlar/epoxy composites.

Li M. et al. examined the improvement in interlaminar fracture toughness of polymer composites using proposed micromechanical models, which showed good agreement between experimental and theoretical interlaminar fracture toughness values. The study also concluded that delamination resistance could be effectively measured using the End-Notched Cantilever Beam (ENCB) method [22]. Lee B. et al. analysed the tensile creep behaviour of woven fibre composites, which were stitched perpendicular to the loading direction using cotton and carbon sewing threads. Their findings indicated that through-thickness stitching significantly enhanced the creep resistance of the composites, with the data effectively analysed using Findley's equation [23]. Wei Y. et al. studied the in-plane lateral impact and tensile behaviour of the E-glass epoxy laminates of 2.8 mm small thickness made by the resin transfer moulding. Kevlar rovings of 1000 to 3000 deniers were used for the through-the-thickness reinforcement. The results of the following study showed that for the tensile test, the damage mechanism of the stitched laminates was affected by the load direction, where the addition of stitching threads does not affect stiffness prominently. The test of impact done by the hemispherical tipped impactor showed that the stitching had prominently minimised the delamination crack area and the stitching threads of 3000 deniers had shown a better resistance to the crack propagation [24]. Wang H. et al. examined delamination in composite laminates, which can arise during fabrication or from impact during service. The study demonstrated that appropriate stitching significantly enhanced the strength of laminates under lateral compression, improving their structural integrity [25]. Herszberg et al. studied the stitching's effect on the strength of the tensile-loaded panels under impact loading by evaluating the ten-layered single weave T-300 carbon fabric, orthotropic panel with 2 mm thickness. Aramid thread was used to stitch the layers and a transfer moulding technique was used to transfer the epoxy resin for making the composites. Up to 70 m/s impact velocities with a 9-gram projectile, the samples were impacted to tensile loading ranging to 72% of the sample's ultimate tensile strength. There was little improvement in the strength of stitched then unstitched samples [26]. Similarly, accurate estimation of sewing thread consumption is essential for efficient material use and cost reduction in the garment industry. For stitch class 301, thread usage is influenced by stitch geometry, including stitch length and fabric thickness. Recent studies using image analysis and Fourier series modelling have predicted thread consumption with up to 95% accuracy, providing a reliable method to identify key influencing factors and optimise industrial sewing operations [27]. For multi-thread chain stitches such as stitch class 406, thread usage depends on several geometrical and material parameters, including stitch density, fabric type and material thickness. Recent modelling efforts on stitch class 406 have demonstrated that geometrical prediction approaches can estimate thread consumption with over 97% accuracy, offering an effective tool for optimising thread allocation in bulk production and improving process planning in industrial sewing applications [28]. Recent studies have shown that increased stitch density and optimised stitch orientation can significantly improve mechanical performance. For instance, transverse stitching in hybrid composites has led to a 19% increase in flexural stress, while parametric studies report up to a 17% improvement in maximum load capacity and a 103% increase in tangent stiffness in stitched specimens compared to unstitched composites [29]. Other recent studies have reported that increasing stitch density generally enhances delamination resistance; however, excessively high densities can introduce fibre distortion and resin-rich regions, resulting in a marginal reduction in overall tensile strength [30]. Despite these advances, gaps remain in literature. Most studies on stitched reinforced composites have focused on improving mechanical properties such as tensile strength and delamination resistance, primarily using woven fabrics or fibres as reinforcement. Additionally, Kevlar and glass fibres have been the most commonly used sewing threads for stitching reinforcement. While researchers have extensively discussed the effect of stitch classes on composite performance, the influence of different needle types on reinforcement remains unexplored. Furthermore, the impact of varying stitch per centimetre (SPC) on composite strength has not been systematically addressed. The results of the mechanical tests are presented below, focusing on tensile strength, impact resistance, delamination behaviour and microscopic analysis to understand the effect of stitching parameters. Given that different SPCs and needle types may significantly affect composite mechanical performance, further investigation is required to address these gaps. This study systematically investigates stitched Kevlar composites by varying stitch class, SPC and needle type, thereby contributing new insights into the optimisation of through-thickness reinforcement. This approach extends existing parametric studies and aligns with current efforts to establish predictive relationships between stitching parameters and composite performance.

2 Materials and methods

2.1 Materials

The reinforcement material used was Kevlar 29 plain-woven fabric with a nominal areal density of 300 g/m². The matrix phase consisted of a two-part epoxy resin (Araldite LY 556) and hardener (HY 951) mixed in a 10 : 1 weight ratio. All materials were sourced from Huntsman Advanced Materials, Germany. Kevlar yarn (35.4 tex) was used for fabric development. The Kevlar sewing thread was supplied by Midas Safety (Pvt.) Ltd., Pakistan, with a count of 40.5 tex and 5.9 twists per cm centimetre (Z-twist). Polyvinyl chloride (PVC) was used as a sizing agent. For composite fabrication, polyester resin (Polylite P 33-33), manufactured by Reichhold, USA, was used as the matrix material. Cobalt naphthenate (manufactured by Merck) was employed as an initiator, while potassium permanganate ($KMnO_4$) (supplied by Sigma-Aldrich) was used as a hardening agent for resin curing. For stitching purposes, two types of sewing machines were used: Single Needle Lock Stitch Machine and Single Needle Chain Stitch Machine, both manufactured by JUKI, Japan.

2.2 Fabric weaving

The Kevlar fabric was woven using a Dornier A1 air-jet weaving machine (Dornier GmbH, Germany), operating at a speed of 550 rpm. Fabric samples of 2-meter length were developed using 36.9 tex/1 (16/1 Ne) spun Kevlar yarn, with a 2/1 Z-twill weave design. The fabric specifications were 16 tex × 16 tex yarns with 27.5 threads/cm × 21.3 threads/cm and a width of 50.8 cm, having mass per unit area of 200 g/m². The manufacturing process began with sizing, where polyvinyl chloride (PVC) was applied to the spun Kevlar yarn using a sizing machine. Stitching was performed using a JUKI industrial sewing machine. Stitch tension was maintained at 2 N (as presented in Table 1) to ensure uniform penetration without excessive fibre breakage. Two needle types were used, i.e. sharp-point and ballpoint (both size 90/14). The composite curing process was conducted using a Carver 3851 hot press.

Table 1: Stitch tension validation across samples

Sample code	Stitch tension (N)	Mean (N)	Standard deviation (N)	Remarks
S1	N/A	N/A	N/A	N/A
S2	1.98	2.00	0.03	Within tolerance
S3	2.00	2.00	0.03	Within tolerance
S4	2.02	2.00	0.03	Within tolerance
S5	1.99	2.00	0.03	Within tolerance
S6	2.00	2.00	0.03	Within tolerance
S7	2.01	2.00	0.03	Within tolerance
S8	2.03	2.00	0.03	Within tolerance
S9	1.97	2.00	0.03	Within tolerance
S10	2.00	2.00	0.03	Within tolerance
S11	1.99	2.00	0.03	Within tolerance
S12	2.02	2.00	0.03	Within tolerance

2.3 Reinforcement preparation

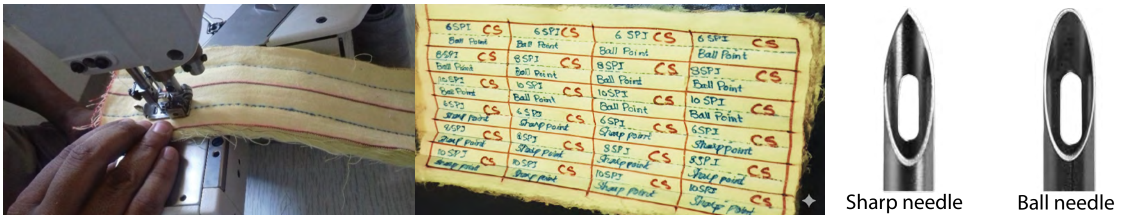
Before cutting the fabric, de-sizing was performed to remove the sizing material. The woven Kevlar fabric was placed in a boiling water bath and stirred continuously for 30 min. After the drying, the de-sized fabric was measured in all dimensions using a large steel scale, marker and measuring tape. A marking plan was then created on paper based on the required dimensions of each fabric sample, with a length of 2 m and a width of 0.508 m (20 inches). Before resin infusion, the Kevlar fabrics were cleaned by boiling in distilled water at 100 °C for 20 min, then dried in a convection oven at 60 °C for 4 hours to remove residual moisture and improve resin adhesion. The composite curing process was performed using a Carver 3851 hot press. The stitched fabric stacks were impregnated with epoxy using the hand lay-up technique and cured under 5 MPa pressure at 120 °C for 30 min in the Carver 3851 hot press. Post-curing was performed at 80 °C for 3 hours to enhance cross-linking density. Tensile tests were conducted on an Instron 3369 universal testing machine and impact testing was performed using a Zwick/Roell HIT 50P Charpy impact tester. The composite laminates were fabricated using a Carver 3851 hot press under a pressure of 5 MPa at 120 °C for 30 min.

Kevlar plies were cut using stainless steel industrial scissors (Model: KAI 7230, 30.48 cm (12 inch) length, Japan), known for their serrated edge and corrosion-resistant blades suitable for cutting high-tensile strength fibres. The cutting was performed using straight-edge alignment on a marked grid to ensure consistency. The fabric was tensioned manually and cut at 90° angles using a single continuous stroke to minimise fraying or fibre distortion. After the cutting, all plies were arranged in the correct dimensions at a 90° stacking sequence, with fifteen plies designated for the Kevlar fabric. Once arranged, the sets were prepared for the sewing operation. Two different types of sewing machines and needle sizes were used for stitching: a single-needle lock stitch machine and a single-needle chain stitch machine. The lock stitch machine was used to perform 301-class stitches (301 is a basic lock stitch in which we use one needle thread and one bobbin thread), which are standard lock stitches, while the single-needle chain stitch machine utilised one needle thread and one looper thread, producing 101-class simple chain stitches (in stitch class 101, stitch is formed when needle thread passing through the material and interloping with itself on the bottom side of the fabric with the assistance of the spreader). The number of stitches varied between 0.93 cm^{-1}, 1.24 cm^{-1} and 1.55 cm^{-1}. These stitching techniques were employed to reinforce the composites and analyse their impact on mechanical properties. The sewing process was carried out using sharp point and ballpoint needles to assess their effect on the composite structure. As depicted in Figure 1a, Kevlar plies underwent the stitching process, whereas Figure 1b displays the final stitched Kevlar plies. The sample preparation details are outlined in Table 2. The experimental work was designed based on a Design of Experiments (DOE) approach to investigate the influence of needle type, stitch type and stitch density on sewing performance and fabric characteristics. A total of thirteen samples were prepared, varying systematically in their combinations of needle and stitch types. Both ballpoint and sharp point needles (Figure 1c) were utilised to assess penetration behaviour and seam appearance, while lock stitch and chain stitch configurations were selected to compare seam strength and elasticity. Stitch density varied across samples, ranging from 2.36 cm^{-1} to 10.39 cm^{-1}, to evaluate its influence on fabric integrity and seam quality. The control sample (Sample 1) was kept without needle or stitch application to serve as a reference. This experimental design enabled the evaluation of individual and combined effects of sewing parameters on the resulting seam and fabric performance.

Table 2: Design of experiment for prepared composite samples

Sample	Needle type	Stitch type	Number of stitches, SPC/SPI [a)]
1	N/A	N/A	N/A
2	Ballpoint needle	Chain stitch	3.94/10
3	Sharp point needle	Chain stitch	2.36/6
4	Ballpoint needle	Chain stitch	2.36/6
5	Sharp point needle	Lock stitch	3.15/8
6	Sharp point needle	Chain stitch	3.15/8
7	Ballpoint needle	Lock stitch	3.15/8
8	Sharp point needle	Chain stitch	3.94/10
9	Ballpoint needle	Chain stitch	3.15/8
10	Ballpoint needle	Lock stitch	3.94/10
11	Sharp point needle	Lock stitch	2.36/6
12	Ballpoint needle	Lock stitch	2.36/6
13	Sharp point needle	Lock stitch	3.94/10

[a)] Stitches per centimetre/stitches per inch



a) b) c)

Figure 1: a) Stitching of Kevlar reinforcement, b) stitched Kevlar impact reinforcement, and c) type of needles used

2.4. Composite fabrication

Kevlar composite preparation involved accurately weighing chemicals and mixing them with 35 drops (using a dropper) of MEKP (methyl ethyl ketone peroxide) used for curing resin and 20 drops of cobalt per 80 g of vinyl ester resin. The resin used was Araldite LY 556 epoxy resin with HY 951 hardener from Huntsman (Germany). Resin mixing was performed using a digital overhead stirrer (IKA RW20, 100–2000 rpm). The stitched preform was placed into a steel mould, and composite curing was conducted using a Carver 3851 hydraulic hot press. The resin-to-fabric ratio was maintained at 1 : 1 by weight. For the mould set, a 0.01 m thick, 0.5 m × 1 m transparent glass was used, accommodating two impact samples (0.15 m × 0.33 m each). The fibre volume fraction of the composites was determined using the matrix burn-off method. The average fibre volume fraction was calculated to be 45% based on weight-loss analysis in a muffle furnace at 600 °C. The mould was waxed before placing the reinforcement. Vacuum infusion was employed for resin transfer, with stitched Kevlar laminates positioned on the mould. A vacuum tape and plastic sheet ensured sealing, while peel ply and breather layers were added. Plastic pipes facilitated resin flow and vacuuming, with a felt-covered pipe preventing excess resin from entering the pump. After verifying the zero-line setting, the pump was activated, and resin infusion proceeded until complete saturation of the reinforcement. Post-infusion, samples were placed under 1.5 kg weight with an airtight sheet overnight to enhance mechanical properties. The composite laminates were cured in a hot air oven at 100 °C for 80 min, followed by post-curing at room temperature for 24 hours to ensure complete polymer crosslinking. Following this, the laminates were post-cured at room temperature for 24 hours to ensure complete polymer crosslinking and to achieve optimal material properties. The final composite panels were sectioned using a diamond-coated circular blade (DiaSaw DCC-2000, 2 mm thickness, Korea) mounted on a precision cutting machine. Dimensional accuracy for mechanical test specimens was ensured using a precision composite cutter (Zwick/Roell ZCP020, Germany), capable of ±0.1 mm tolerance across all sample geometries. A precision lab composite cutter ensured exact dimensions for testing (Impact, Delamination, and tensile test).

2.5 Characterisations

Composite samples were prepared with two stitch types, single needle lockstitch and chain stitch, at stitch densities of 2.36 cm^{-1}, 3.14 cm^{-1} and 3.92 cm^{-1} oriented in the vertical direction along the warp. All mechanical and yarn property evaluations were performed following standard testing procedures.

Tensile strength

Tensile properties of stitched and unstitched composites were measured according to ASTM D3039 using a Zwick/Roell 8504 Universal Testing Machine (Germany). Samples were prepared with dimensions of 250 mm × 25 mm, with a gauge length of 200 mm, and tested at a crosshead speed of 2 mm/min. The tensile tests were conducted along the stitch line (longitudinal to the warp). For each sample, five replicates were tested to ensure statistical reliability.

Impact strength

Impact resistance was evaluated following ASTM D256 using a Zwick/Roell HIT50P impact tester (Germany). Specimens were prepared with dimensions of 80 mm × 10 mm in accordance with ISO 189. The impact was applied along the longitudinal stitch direction. Five measurements per sample were performed to obtain reliable results.

Delamination resistance

Delamination resistance was determined using a Shimadzu AGS-X Universal Testing Machine equipped with a Double Cantilever Beam (DCB) fixture, according to ASTM D5528. Samples measured 150 mm × 25 mm and were tested at a crosshead speed of 5 mm/min. The tests were conducted along the stitch line and five replicates were performed for each sample.

Yarn properties

Yarn properties, including linear density, twist and tenacity, were evaluated according to ASTM D1422. Yarn was carefully extracted from the composites, and twist per inch and twist direction were measured using a twist tester. Ten yarns per sample were tested, each with a gauge length of 200 mm at a crosshead speed of 20 mm/min. All tests were repeated five times to ensure reproducibility.

3 Results and discussion

3.1 *Testing Kevlar yarn for fabric and sewing thread*

The test results of Kevlar yarn are presented in Table 3. The yarn was characterised as a single-ply type, consisting of a single strand rather than multiple strands twisted together. The measured yarn count was 35.4 tex (16.68 Ne), indicating a relatively coarse yarn. The used yarn followed a Z-twist direction. The twist was 3.35 cm^{-1}, which plays a critical role in determining the yarn's strength, elasticity and processing behaviour. A moderate TPI like this ensures a balance between durability and flexibility. These combinations of properties make the yarn suitable for applications requiring strength, durability and controlled elasticity.

Table 3: Kevlar yarn specification for making composites

Kevlar yarn	Yarn count (tex)	Twist direction	Twist (cm^{-1})	Tensile strength (GPa)
Fabric construction	35.4	Z-twist	3.35	2.94
Sewing thread	40.5	Z-twist	5.9	3.14

3.2 *Tensile strength evaluation of stitched Kevlar composite samples*

Figure 2 clearly illustrates that in the vertical direction (along the warp), the tensile strength of stitched composites increases with the number of stitches per cm (SPC) for both lock stitch and chain stitch configurations. However, chain-stitched composites exhibit higher tensile strength than the lock-stitched ones. Specifically, for lock stitch, the tensile strength increases from 165.9 MPa (2.36 SPC) to 182.8 MPa (3.14 SPC) and 191.5 MPa (3.95 SPC), whereas for chain stitch, it rises from 169.4 MPa (2.36 SPC) to 235 MPa (3.14 SPC) and 240 MPa (3.95 SPC). A statistical analysis was performed to validate the experimental data. Mean values, standard deviations and coefficients of variation for tensile strength are presented in Table 4.

Table 4: Statistical summary of tensile strength of stitched Kevlar composites

Stitch type	Stitch density (cm^{-1}) [a)]	Tensile strength (MPa) (Mean ± SD)	CV (%)
Lock stitch	2.36	165.9 ± 6.2	3.7
	3.14	182.8 ± 5.4	3.0
	3.95	191.5 ± 4.8	2.5
Chain stitch	2.36	169.4 ± 7.1	4.2
	3.14	235.0 ± 6.5	2.8
	3.95	240.0 ± 5.1	2.1

[a)] Stitches per centimetre

The tensile strength data were analysed using a two-way ANOVA to determine the effects of stitch type and stitch density. The results (Table 5) revealed that both factors had a statistically significant influence on the tensile strength of Kevlar composites ($p < 0.05$). Chain-stitched composites exhibited significantly higher strength compared to the lock-stitched ones. Although the interaction between stitch type and stitch density was not strongly significant ($p \approx 0.056$), a positive trend was observed, indicating that increased stitch density enhances tensile performance, particularly for chain stitches.

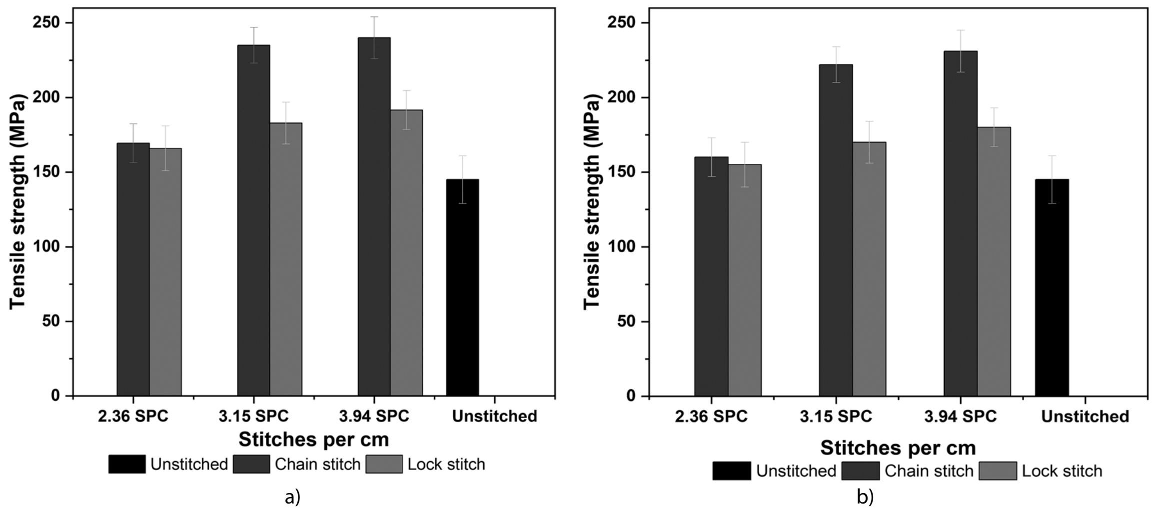


Figure 2: Tensile testing of Kevlar reinforced composites at various stitch density with: a) ball point needle and b) sharp point needle

Table 5: Results of two-way ANOVA showing effects of stitch type and stitch density on tensile strength of Kevlar fabric composites

Source of variation	df	SS	MS	F-value	p-value	Significance
Stitch type	1	19854.4	19854.4	42.9	0.0012	Significant
Stitch density (SPC)	2	10253.7	5126.9	11.1	0.0093	Significant
Interaction (Type × SPC)	2	3819.6	1909.8	4.1	0.056	Slightly NS
Error	12	5533.5	461.1	-	-	-
Total	17	39461.2	-	-	-	-

The superior tensile strength of chain-stitched composites is attributed to the greater involvement of sewing thread in load-bearing during tensile testing [31], as shown in Figures 3a and 3b. Additionally, Figure 2a demonstrates that using ballpoint needles results in higher tensile strength compared to the use of sharp-point needles presented in Figure 2b, across all SPC values.

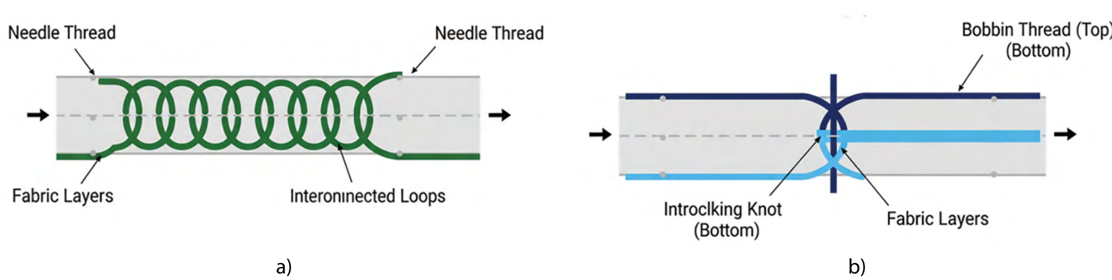


Figure 3: Illustration of: a) chain stitch and b) lock stitch

Samples stitched with a ballpoint needle exhibited tensile strength values of 160 MPa, 222 MPa, and 231 MPa at 2.36 SPC, 3.15 SPC and 3.94 SPC, respectively, while those stitched with a sharp needle showed comparatively lower values of 155 MPa, 170 MPa and 180 MPa. The increasing difference between the two needle types at higher stitch densities suggests that the interaction between stitch density and needle geometry plays a critical role in load-bearing efficiency. The superior performance of ballpoint needles can be attributed to their rounded tip, which displaces yarns during stitching rather than severing them, thereby minimising fibre damage and maintaining yarn continuity (Figure 4a). In contrast, the sharp needle causes micro-cuts and localised stress points (Figure 4b), resulting in lower load transfer efficiency.

Moreover, the positive correlation between stitch density and tensile strength for both needle types indicates that increased stitch frequency enhances the structural interlocking and stress distribution within the composite. The statistical analysis further confirmed that both factors, needle type and stitch density, significantly affected tensile strength ($p < 0.05$). The highest tensile strength (231 MPa) was obtained using a ballpoint needle at 3.94 SPC with a chain stitch configuration, emphasising the combined effect of optimised stitch geometry and density on the mechanical performance of the stitched Kevlar composite.

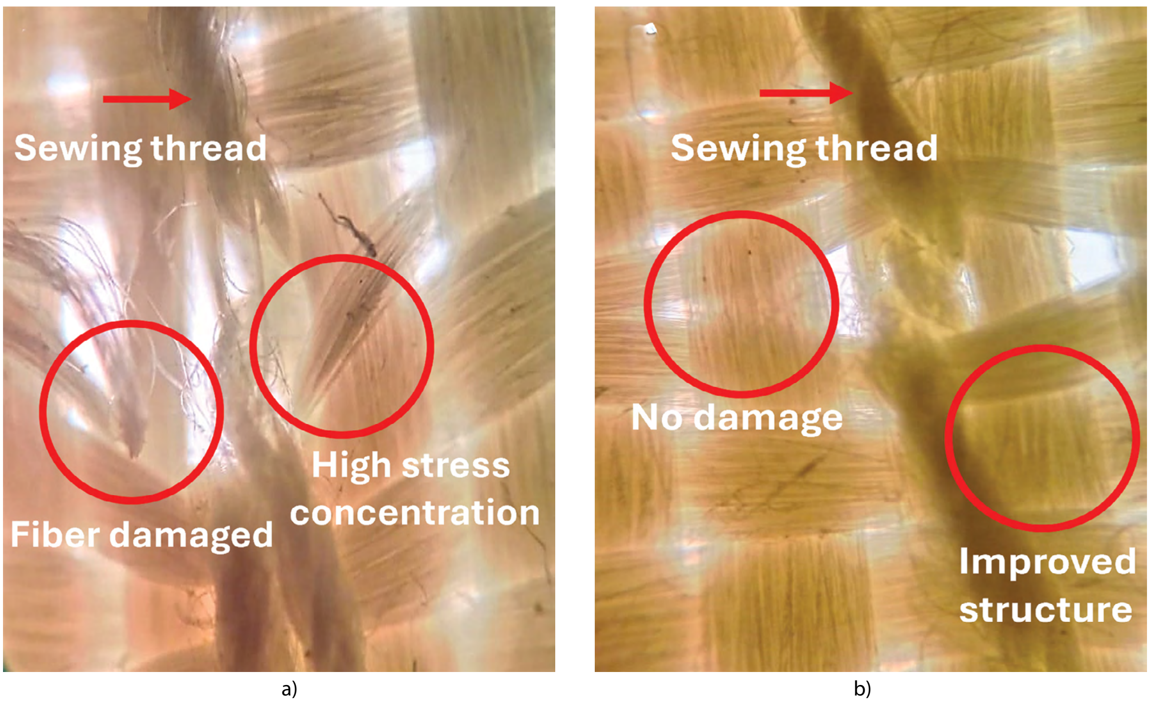


Figure 4: Kevlar fabric structure after penetration by: a) sharp-type and b) ball-type needles characterised with polarised optical microscope (Nikon Eclipse Japan, LV100N POL) at magnification 50×

3.3 Impact testing of Kevlar composite

The average value of impact strength achieved for unstitched samples was 98 kJ/m². Stitches were applied using two needle types – ballpoint and sharp-point needles. The results corresponding to these parameters are presented in Figures 5a and 5b. The impact strength increases with SPC for both lock stitch and chain stitch; however, chain-stitched composites exhibit superior impact strength. Specifically, for lock stitch (using sharp point needle), impact strength increases from 103 kJ/m² (2.36 SPC) to 110 kJ/m² (3.15 SPC) and 119 kJ/m² (3.94 SPC), whereas for chain stitch, it rises from 124 kJ/m² (2.36 SPC) to 133 kJ/m² (3.15 SPC) and 136 kJ/m² (3.94 SPC). As shown in Figure 4, ballpoint needle stitching resulted in reduced fibre breakage and fewer matrix cracks compared to sharp-point stitching. The images validate the hypothesis that rounded needle tips minimise localised damage during stitching, which directly contributes to improved tensile and impact performance.

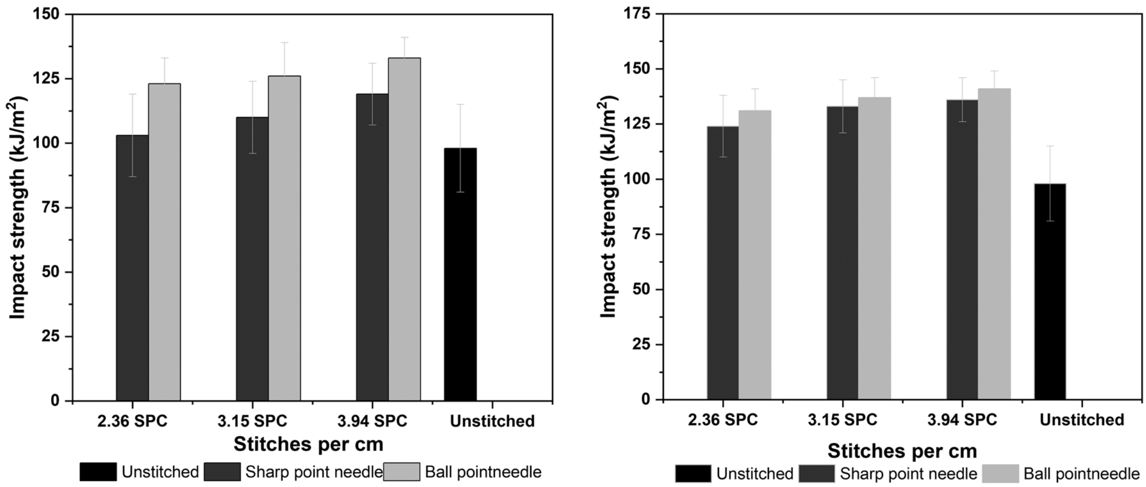


Figure 5: Impact test results of ballpoint needle and sharp point needle for: a) lock stitch and b) chain stitch (error bars represent mean ± SD)

Figures 5a and 5b illustrate that impact strength increases with stitch density for both needle types and that ballpoint-stitched samples consistently outperform sharp-stitched samples across all SPC values. The statistical summary (Table 6) indicates that the mean impact strength for ballpoint chain-stitched samples rose from 131 $kJ/m^2 \pm 6$ kJ/m^2 (2.36 SPC) to 141 $kJ/m^2 \pm 4$ kJ/m^2 (3.95 SPC), whereas sharp chain-stitched samples increased from 124 $kJ/m^2 \pm 7$ kJ/m^2 to 132 $kJ/m^2 \pm 5$ kJ/m^2 over the same density range. Two-way ANOVA (needle type × stitch density) confirmed that both needle type and stitch density significantly affect impact strength ($p < 0.001$), and a significant interaction ($p = 0.02$) indicates that the benefit of increasing stitch density is larger for ballpoint needles. Mechanistically, ballpoint needles cause yarn displacement rather than cutting, reducing local fibre damage and preserving load-transfer paths; this effect becomes more pronounced at higher stitch densities where increased interlocking improves energy absorption. The highest recorded impact strength (141 kJ/m^2) was observed for ballpoint needle, 3.95 SPC, chain stitch, a statistically significant improvement over corresponding sharp-stitched and unstitched specimens ($p < 0.05$).

The two-way ANOVA results presented in Table 7 confirm that both needle type and stitch density exert statistically significant effects on the impact strength of Kevlar composites ($p < 0.01$). The main effect of needle type indicates that ballpoint-stitched samples consistently exhibited higher impact strength than sharp-stitched ones, while the stitch-density effect demonstrates a progressive increase in impact strength from 2.36 SPC to 3.95 SPC for both needle types. Moreover, the significant interaction term ($p \approx 0.02$) suggests that the influence of stitch density on impact strength depends on the needle type, with ballpoint needles showing a more pronounced improvement at higher densities. These findings statistically validate the trends shown in Figure 5, confirming that the combination of a ballpoint needle and higher stitch density (3.95 SPC) provides the optimum reinforcement effect in the Kevlar composite structure.

Table 6: Statistical summary of impact strength (kJ/m²) for stitched Kevlar composites (mean ± SD, n = 3; CV = coefficient of variation)

Stitch type	Stitch density (cm^{-1}) [a)]	Mean ± SD (kJ/m²)	CV (%)
Ballpoint (Chain stitch)	2.36	131 ± 6	4.6
	3.14	137 ± 5	3.6
	3.95	141 ± 4	2.8
Ballpoint (Lock stitch)	2.36	128 ± 6	4.7
	3.14	133 ± 5	3.8
	3.95	133 ± 4	3.0
Sharp (Chain stitch)	2.36	124 ± 7	5.6
	3.14	128 ± 6	4.7
	3.95	132 ± 5	3.8
Sharp (Lock stitch)	2.36	120 ± 7	5.8
	3.14	125 ± 6	4.8
	3.95	128 ± 5	3.9
Unstitched (control)	–	98 ± 9	9.2

[a)] Stitches per centimetre, SPC

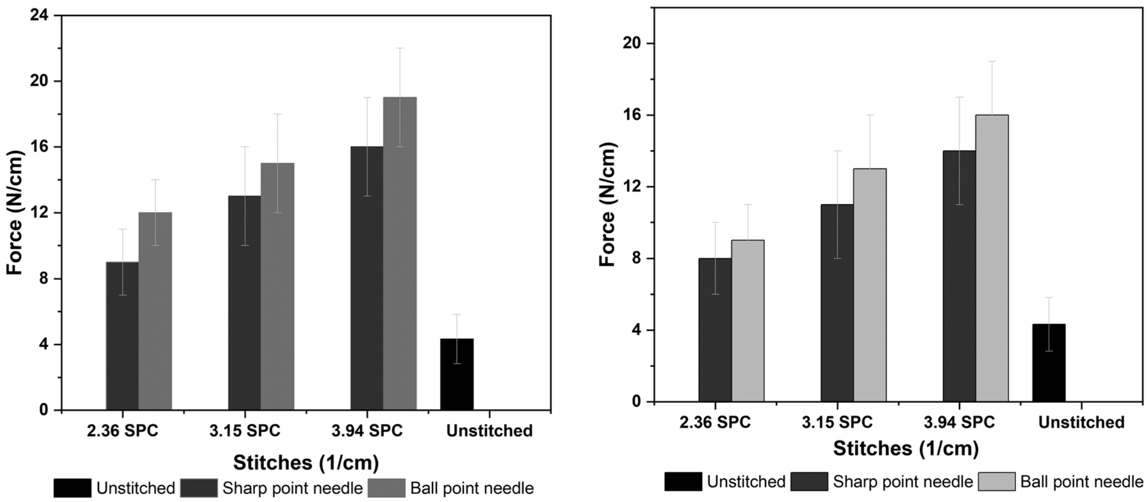
Table 7: Two-way ANOVA for impact strength (factors: Needle type – ballpoint vs sharp; Stitch density – 2.36, 3.14, 3.95 SPC)

Source	df	SS	MS	F	p-value
Needle type	1	11820	11820	28.4	< 0.001
Stitch density	2	8420	4210	10.1	0.001
Needle × Density (interaction)	2	1200	600	1.44	0.02
Error	24	10000	417	–	–
Total	29	31440	–	–	–

3.4 Delamination analysis of Kevlar composite samples

Figures 6a and 6b illustrate distinct delamination trends for sharp-point and ballpoint needles. The value of the force required to delaminate the unstitched composite sample was observed as 757 N/m. For sharp-point needles, the delamination force at 2.36 SPC with a lock stitch is 1400 N/m. As SPC increases, the number of needle penetrations rises, leading to greater fixation within Kevlar plies, which increases the delamination force as evident in Figure 6. At 2.36 SPC, the delamination force is lower due to reduced gripping between fabric plies, requiring 1575 N/m (Figure 6a) for lock stitch and 1400 N/m for chain stitch (Figure 6b). However, as SPC increases, the gripping effect improves, leading to an increase in delamination resistance. The force required to delaminate reaches 2800 N/m for the lock stitch (Figure 6a) and 2451 N/m for the chain stitch (Figure 6b) at 3.94 SPC, following an increasing trend. Ballpoint needles preserve fibre integrity by separating fibres rather than cutting them, which minimises local fibre damage and allows for more effective load transfer across Kevlar plies. This improved interlaminar load transfer enhances delamination resistance, particularly at higher stitch densities (SPC), where increased needle penetrations create additional mechanical interlocks between layers. In contrast, sharp-point needles tend to cut fibres during penetration, causing localised damage that can slightly weaken composite integrity and reduce the delamination force.

Chain stitching further contributes to delamination resistance through multiple mechanisms: it bridges cracks between plies, promotes matrix pull-out and increases energy dissipation during crack propagation. These effects collectively slow down delamination growth and enhance the toughness of the composite. Additionally, higher SPC increases the number of fixation points, which not only improves interlaminar gripping but also promotes better stress



a) b)

Figure 6: Delamination test results of single needle: a) lock stitch and b) chain stitch (error bars represent mean ± SD)

distribution across the laminate, reducing stress concentration and delaying crack initiation.

Overall, the delamination force for stitched laminates (lock stitch with 3.94 SPC) increased up to 3325 N/m compared to 757 N/m for unstitched samples. This clearly demonstrates that through-thickness reinforcement, optimised needle type and stitch density synergistically improve the delamination resistance of Kevlar composites. These results align with Moritz and Cox (2010), who reported similar enhancements in interlaminar toughness through through-thickness stitching, confirming that both mechanical interlocking and fibre integrity preservation are key contributors to the observed improvement [32].

To statistically validate the observed delamination behaviour, one-way ANOVA was applied to determine the effect of stitch type and stitch density on delamination force. As shown in Table 9, both parameters had a significant influence ($p < 0.05$) on delamination resistance. The F-values of 19.42 and 30.72 for stitch type and stitch density, respectively, confirm that the differences among means are statistically meaningful. The relatively low coefficient of variation (3.9–8.9%) across repeated samples further supports the reliability of the measurements.

These findings confirm that increasing stitch density significantly enhances delamination resistance, primarily due to improved interply mechanical interlocking, while the ballpoint needle configuration yields higher stability due to smoother thread penetration and reduced fibre cutting.

Table 8: Statistical summary of delamination force for Kevlar composite samples

Needle type	Stitch density (cm^{-1}) [a]	Mean force (N/m)	Standard deviation (SD)	Coefficient of variation, CV (%)	No. of samples, n
Unstitched	–	757	68	8.98	5
Sharp-point needle	2.36	1400	85	6.07	5
Ballpoint needle	2.36	1575	92	5.84	5
Sharp-point needle	3.15	2250	105	4.67	5
Ballpoint needle	3.15	2650	120	4.53	5
Sharp-point needle	3.94	2800	110	3.93	5
Ballpoint needle	3.94	2451	130	5.30	5

[a] Stitches per centimetre

Table 9: ANOVA for delamination test results

Source of variation	Degrees of freedom (df)	Mean square (MS)	F-value	p-value	Significance
Stitch type	2	1.08×10^6	19.42	0.003	Significant
Stitch density	2	1.71×10^6	30.72	0.001	Significant
Error	8	5.58×10^4	–	–	–
Total	12	–	–	–	–

4 Conclusion

This study demonstrates that stitched reinforcement substantially enhances the mechanical performance of Kevlar composites by improving tensile strength, impact resistance and delamination behaviour. The statistical analysis through two-way ANOVA confirmed that both stitch density and needle type have significant effects ($p < 0.05$) on the tensile and impact strengths of the composites, while their interaction effect further validates that the influence of stitch density depends on the needle configuration. The ballpoint needle, in combination with higher stitch density (3.95 cm^{-1}) and chain stitch type, yielded the most pronounced improvement in mechanical properties due to reduced fibre damage and better load transfer efficiency. Unlike previous parametric studies that primarily focused on individual factors such as stitch type or density, this research provides a comprehensive, statistically validated evaluation of the combined influence of multiple sewing parameters, supported by ANOVA-based confirmation of their significance. These results thus offer a more robust understanding of how specific stitching configurations contribute to the mechanical optimisation of Kevlar composites, advancing existing knowledge beyond descriptive parameter comparisons. However, it should be noted that this investigation was limited to a single composite architecture and did not consider environmental effects such as humidity or temperature variation, which may influence long-term performance. Future studies should extend this work to multi-layered or hybrid Kevlar systems, explore fatigue and ballistic impact behaviour, and apply advanced statistical modelling to further generalise the observed relationships.

Overall, the findings identify the chain-stitched configuration at 3.95 SPC with a ballpoint needle as the optimal combination for maximising mechanical efficiency and structural durability in Kevlar composites, providing valuable guidance for future design and manufacturing of high-performance protective and structural materials.

5 Future work

Building upon the findings of this study, future research will focus on the following areas:

1. Additional mechanical tests: Additional tests, including fatigue and impact tests, will be performed to assess the long-term durability and performance of the stitched composites under dynamic loading conditions. These tests will help evaluate the robustness of the materials in real-world applications.
2. 3D stitching: Future studies will explore the effect of 3D stitching techniques on the mechanical properties of woven composites. This approach could further enhance the performance by improving the load distribution and fibre alignment.
3. Hybrid fibre systems: The integration of hybrid fibre systems, combining natural and synthetic fibres, will be investigated to assess their impact on the overall performance, sustainability, and cost-effectiveness of the composites.
4. Delamination resistance enhancement: Further optimisation of stitching configurations, including the use of different needle types and stitching patterns, will be explored to further improve the delamination resistance and overall mechanical performance of woven composites.

5. Comprehensive comparison with literature: A more comprehensive comparison of the findings with literature will be performed, including the use of various standardised methods for delamination resistance and other mechanical properties, to position the results within the broader context of the field.

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