

Development of conductive composite materials for high voltage applications

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Abstract

Conductive stitching using soft conductive yarn has been developed to enhance the electrical conductivity of carbon fibre-reinforced polymers (CFRPs), to provide versatility for high-voltage applications, including potential lightning strike protection. To minimise the impact to in-plane mechanical properties associated with high stitching densities, a thin silver-coated carbon fibre veil was integrated with the conductive stitching to further improve the electrical conductivity without requiring an extensive amount of conductive yarn. The integration of conductive stitching with the surface veil reduces the potential of galvanic corrosion and adhesion issues often associated with conventional copper and aluminium lightning strike protection. The results show that the in-plane and through-thickness conductivity of the composites was significantly improved from that of the unstitched composites. Under the high-voltage test, the results demonstrated that integrating a thin conductive surface veil not only reduces the surface damage, but also directs the strike impulse toward the conductive yarns as the main lightning strike protection mechanism. Strength retention results following high-voltage testing demonstrated comparable performance for the conductive composites development when compared to conventional copper mesh specimens. This study provides a new approach to developing high-conductivity structural composites while maintaining sufficient mechanical strength, which has potential for use as conductive structural materials for aircraft lightning strike protection applications.

Keywords: conductive stitching, high-voltage test, strength retention, conductive structural composites

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites have been increasingly used as structural materials specifically for aircraft due to their lightweight, high specific strength, and corrosion resistance [1, 2]. Although composites have been adopted for weight and fuel reduction, they still face challenges that limit their use due to their low interlaminar properties and low electrical conductivity, which make them susceptible to impact loading and natural phenomena such as lightning strikes [3]. This low electrical conductivity commonly requires expanded copper or aluminium mesh to be included in the composite structure to safely dissipate the lightning strike current, which statistically occurs to passenger aircraft once a year [4]. Although this metallic mesh is effective at protecting the aircraft, integrating copper or aluminium materials in CFRPs poses challenges, such as the potential for galvanic corrosion and adhesion problems [5].

There are two main alternative approaches for promoting lightning strike protection of composites. The first approach involves introducing a conductive layer on the composite surface to improve in-plane electrical conductivity, enabling the current to dissipate along the surface [6-10]. The second approach is to enhance the through-thickness conductivity of the composite, allowing the electrical

current to dissipate through the out-of-plane direction [11-15]. Surface conductive layers generally reduce the penetration of damage into the laminate depth. However, the conductive layer does not provide mechanical benefits to the structure, for example in delamination resistance [16]. In contrast, through-thickness reinforcement methods offer the additional advantage of improving the interlaminar properties of composites, particularly delamination resistance, while having the potential for enhanced lightning strike protection [11].

Among various through-thickness reinforcement approaches, stitching stands out as a simple, low-cost method with the potential for automation [17]. Stitching has also been reported to significantly enhance the interlaminar fracture toughness while improving the through-thickness conductivity [18]. Additionally, increasing the electrical conductivity of stitched composites can improve their lightning strike protection capability [12]. However, studies investigating the effects of stitch parameters on lightning strike protection remain limited. Additionally, stitch parameters can affect the mechanical performance in a variable manner. Therefore, a comprehensive investigation is necessary to develop conductive structural composites with a balanced combination of electrical conductivity and mechanical strength suitable for structural applications.

In this work, a silver-coated Vectran® yarn, so called Liberator®, was selected as the conductive yarn for stitching. This material offers high strength, excellent electrical conductivity [19], and lower risk for galvanic corrosion with carbon fibre compared to conventional copper and aluminium meshes [12]. This soft, conductive yarn was stitched in a bidirectional grid pattern, with varying distances between adjacent yarns to create different grid sizes. The smaller grid size (higher stitch density) has the potential to reduce strength [20], impacting the structural integrity of the composites. Hence, a conductive surface veil was also integrated with the stitched composites to investigate the electrical and mechanical performance compared to stitching alone. In this work the developed conductive composites were investigated under high-voltage testing to evaluate the lightning strike protection of the composites. This study provides an alternative, novel method for lightning strike protection of CFRP structures and offers insights into the soft-conductive yarn's ability to dissipate current under high-voltage conditions.

2. Methodology

2.1. Materials and Manufacturing

The composites were manufactured by laying up eight plies of 2x2 twill carbon fibres with the stacking sequence of $[0°]_8$. The stitched preforms were manufactured by using a household sewing machine (Janome My Excel 18W). The conductive yarn, Liberator®, which has linear resistance around 3.3 Ω/m, was obtained from Syscom Advanced Materials, USA. The stitch pattern was a bidirectional stitching pattern, consisting of two perpendicular stitching directions. Stitch pitch, the length between two adjacent stitches in the same row, was kept constant at 2 mm. The stitch grid size or the spacing between two stitching lines was set as 12.5 mm and 5 mm respectively.

For the conductive veil material, 8 gsm carbon fibre veils (ACP Composites, USA) were used as a base material. Silver was deposited on the carbon fibre veil using thermal evaporation using the NanoDep Physical Vapour Deposition machine. The deposition rate was set as 2 Å/s with a 12-rpm rotation for the deposition plate. The obtained thicknesses were 100, 200, 300, and 400 nm. The conductive veil was placed on top of the carbon fibre preforms, with the silver deposited side upwards, and stitched together with the preform using the same stitch parameters as the stitched samples without the conductive veil.

For the composites with conventional copper mesh, the expanded copper mesh was placed on top of the carbon fibre, with glass fibre veils placed in between the carbon fibre and the copper mesh and on top of the copper mesh. This configuration allows for replicating the typical setup for the copper mesh in the aircraft structure [21, 22]. A 98-gsm copper mesh (2 Cu (110) 6-100 FA) was obtained from Dexmet Corporation, USA. The 20-gsm glass fibre veil used in this work was obtained from Trojan Fibreglass, Australia.

The composites were fabricated using vacuum infusion with Raku tool epoxy resin (EL-2203) and amine curing agents (EH-2970-1) from GMS Composites, Australia, with the mixing ratio of 10:3. All

samples were cured at room temperature for 16 hours, followed by post-curing at 120 degrees Celsius for 14 hours.

2.2. Characterisations

For the electrical conductivity test, the samples were cut into square specimens with 50 mm sides. The electrical conductivity of the composites was measured using the two-probe method. The pressure was kept constant to ensure a valid result using a hot-press machine. Before the conductivity measurement, the composite's surfaces were gently polished and coated with silver paste (ProSciTech, Australia) to reduce the contact resistance. The high-voltage test was conducted at the National Measurement Institute (NMI) of the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The waveform for the high-voltage test was a front-chopped impulse with a discharge voltage of 50 kV and a current of 5 kA. The specimen was placed on the aluminium grounded electrode, with the copper electrode situated above at a height of 1 mm from the specimen. The samples for high-voltage testing were cut into square specimens with 100 mm sides. Three-point bending was used to determine the flexural properties of the composites in accordance with ASTM D2344. The span-to-thickness ratio was set as 32:1. The test was performed with the Instron 3369 machine with a 10 kN load cell. The surface-damage characteristic was investigated using the Olympus DSX510 digital microscope and the Hitachi S-3400 scanning electron microscope (SEM) at the Electron Microscope Unit (EMU) within the Mark Wainwright Analytical Centre (MWAC) at UNSW Sydney, Australia.

3. Results and Discussion

3.1. Carbon fibre veil selection

The carbon fibre veils were deposited with varying thicknesses of silver. Silver was selected due to the lower potential of galvanic corrosion with carbon fibre compared to copper, which is commonly used as a lightning strike protection material [12]. The carbon fibre veil without silver deposition (CF_0) has a resistance of around 24.4 Ω/sq. After silver deposition with different thicknesses, the silver-coated carbon fibre veils were investigated under the SEM, and with energy dispersive X-ray spectroscopy (EDS) mapping as shown in Figure 1. It can be seen that with thicker coating layers, the silver coating becomes more uniform with less area of bare carbon fibre veil due to the longer deposition time. Additionally, from the EDS mapping, it can be seen that a high silver coating level was obtained at a 400 nm thickness (CF_400), as less carbon is detected compared to the other sample types.

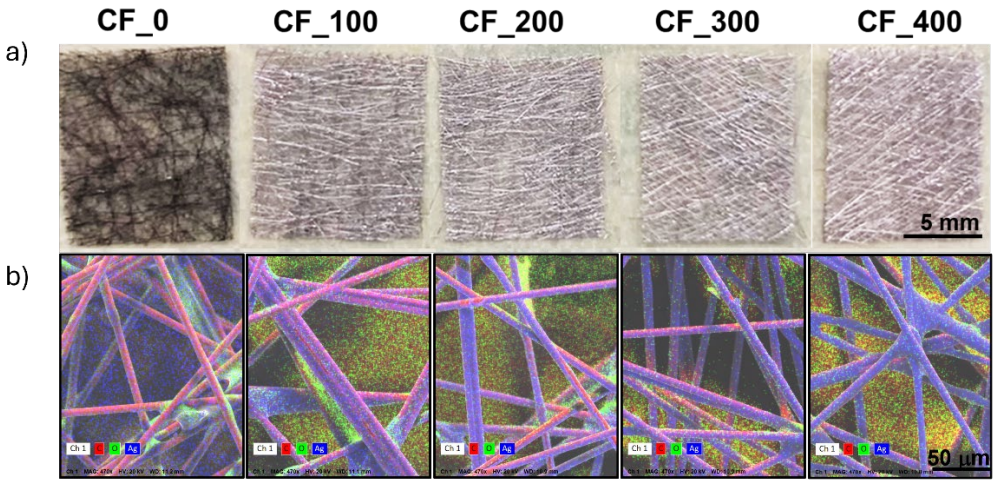


Figure 1 – (a) Physical appearance of different types of CF veils with their corresponding (b) EDS mapping for carbon (red), oxygen (green) and silver (blue).

To determine the optimal coating thickness of the fabricated conductive veil, the sheet resistance value was evaluated with respect to the required materials for deposition, as shown in Figure 2. After silver deposition of 100 nm, the resistance of the carbon fibre veil was reduced to 10.7 Ω/sq from the

24.4 Ω/sq of the CF_0. The resistance continued to drop to 6.9 Ω/sq at 200 nm and reduced to 3.9 Ω/sq at 300 nm. At the higher coating thickness (400 nm), the resistance drops slightly from CF_300 to 3.86 Ω/sq. Given the similar resistance of CF_300 and CF_400, CF_300 was selected as the optimal coating thickness, as it provided the lowest resistance at the minimum weight.

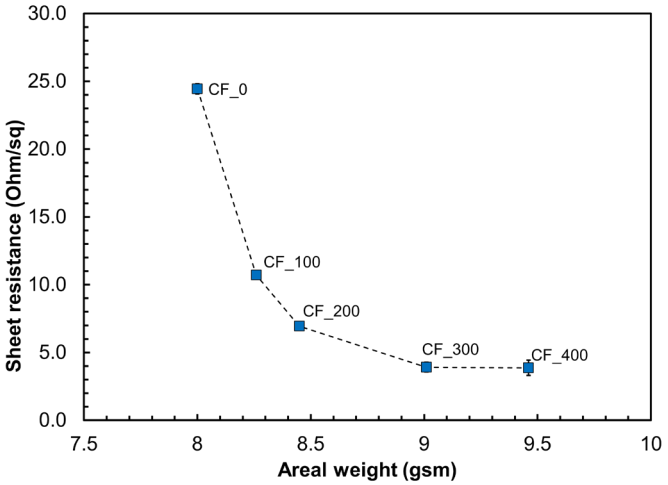


Figure 2 – The relationship between the sheet resistance and areal weight of different coating thickness.

3.2. Composites properties

The most advantageous conductive veil (CF_300) was integrated with the stitched composites to investigate the electrical and mechanical performance. The conductive veil was placed on the top of the carbon fibre fabric layers, with the silver deposited side upwards, and stitched together as shown in Figure 3. Since the conductive veil has a thickness of around 0.05 mm and an areal weight of 9 gsm, the needle can easily pass through to form a stitched preform. These stitched composites with a conductive veil were used to evaluate performance compared to other stitched composites without the conductive layer, composites with copper mesh incorporated on top (CP/Mesh), and unmodified composites (CP). In this work, two types of composites with different grid sizes were used, being 12.5 and 5 mm, denoted as SC12.5 and SC5, to represent composites with moderate and high stitch density, respectively.

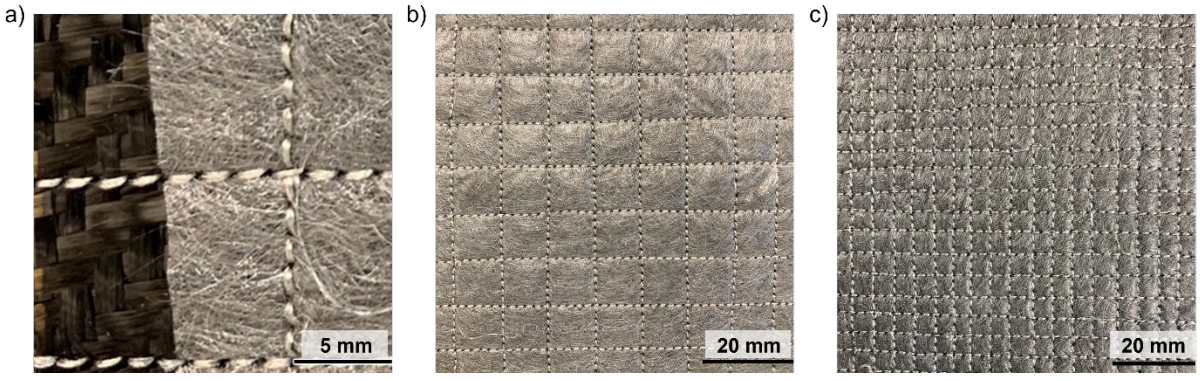


Figure 3 – (a) Stitched preforms comparison of with and without conductive veil, (b) stitched preforms with conductive veil and 12.5 mm grid size, and (c) stitched preforms with conductive veil and 5 mm grid size.

After resin infusion, all the composites have the thickness and the calculated fibre volume fraction as shown in Table 1. It can be seen that both of the thicknesses of the stitched composites with conductive veil (SC12.5CV and SC5CV) did not vary significantly compared to their stitched counterparts. Additionally, the carbon fibre volume fraction decreased after the introduction of the conductive yarns, as the fibre volume fraction was calculated under the assumption that the carbon fibre content remained constant across all samples. As a result, an increase in laminate thickness resulted in a lower overall fibre volume fraction.

Table 1 – Characteristics of different types of composites, including the thickness, calculated fibre volume fraction and yarn volume fraction.

Nomenclature	Conductive layer	Stitch pitch (mm)	Stitch spacing (mm)	Stitch density (1/mm^2)	Laminate thickness (mm)	Calculated fibre volume %	Calculated yarn volume %
CP	-	-	-	-	1.73±0.03	51.8	-
SC12.5	-	2	12.5	0.080	1.87±0.02	47.9	0.91
SC12.5CV	Silver coated veil	2	12.5	0.080	1.87±0.03	47.8	0.91
SC5	-	2	5	0.200	1.98±0.05	45.2	2.21
SC5CV	Silver coated veil	2	5	0.200	1.99±0.02	45.0	2.21
CP/Mesh	Copper mesh	-	-	-	1.91±0.04	46.9	-

3.2.1. Electrical properties

Both in-plane and through-thickness conductivity of the composites were evaluated. The in-plane conductivity was measured in both the longitudinal and transverse directions. For the stitched composites with a 12.5 mm grid size, the number of stitching lines in both longitudinal and transverse directions was the same. However, for the 5 mm grid size, the number of stitching lines was adjusted to maintain a constant stitch density across the laminate thickness for both electrical conductivity and high-voltage testing samples. This adjustment is necessary for precise conductivity evaluation during high-voltage testing, as the high-voltage samples are twice the size of the conductivity samples. Hence, in the electrical conductivity measurement, the SC5 and SC5CV consisted of 10 stitching lines in the longitudinal direction and 9 in the transverse direction to maintain a constant stitch density with the high-voltage samples.

The mean in-plane conductivity value of the different composites investigated is shown in Figure 4b. The unmodified composites (CP) had in-plane conductivities of approximately 4943 S/m and 4896 S/m in the longitudinal and transverse directions, respectively. After integration of conductive yarns, in-plane conductivity increases. SC12.5 increased almost 3.4 times from the CP. When adding the conductive layer to the 12.5 grid size (SC12.5CV), the in-plane conductivity increased by around 25% compared to SC12.5. Higher conductivity enhancement was found with the smaller grid size. The in-plane conductivity of SC5 increased by around 5.5 times and 5.3 times in the longitudinal and transverse directions, respectively, compared to the CP. The addition of the conductive veil to the 5 mm grid size specimen led to comparable in-plane conductivity in the longitudinal and transverse directions, despite the differing stitching lines. This can be attributed to the already high electrical conductivity in the longitudinal direction. Hence, the conductivity improvement from the conductive veil may have a smaller impact than in the transverse direction. However, the improvement of the conductivity in the transverse direction of SC5CV was around 25% from that of SC5. This indicates that the coating layer provides enhancement in in-plane conductivity across stitch densities.

The highest in-plane conductivity among the samples was the CP/Mesh, which demonstrated enhancements of around 10 times and 8.8 times in the longitudinal and transverse directions, respectively, relative to the CP. The difference in conductivity between the two directions is mainly due to the distinct electrical conductivities of the short way of the diamond (SWD) and long way of the diamond (LWD) orientations of the copper mesh. In addition, the orientation and deformation of the copper mesh during handling and manufacturing may also influence the electrical conductivity of the composites.

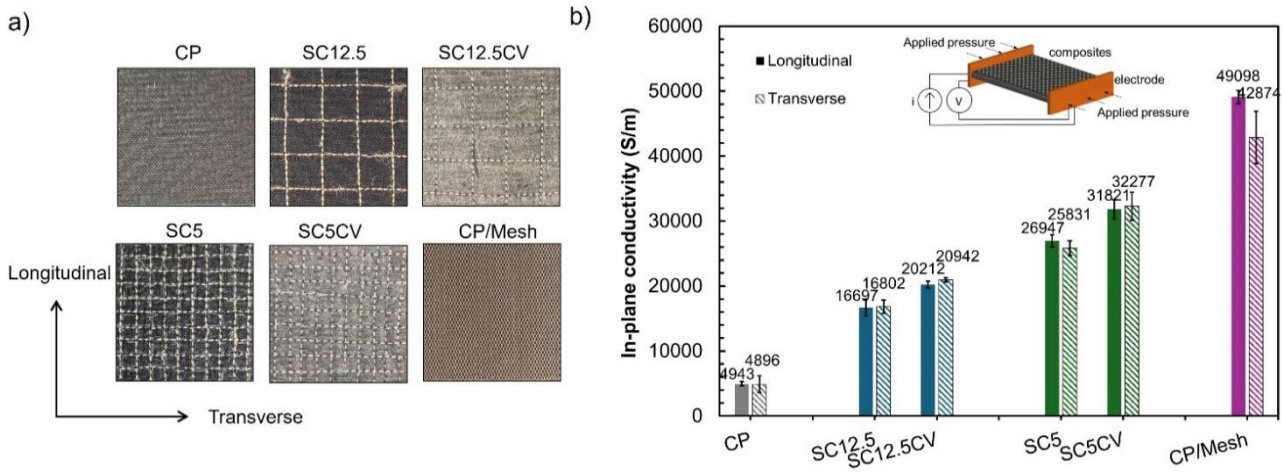


Figure 4 – (a) Different types of samples for electrical conductivity testing, and (b) summary of the in-plane conductivity.

The through-thickness conductivities of the different composites investigated are summarised in Figure 5. The through-thickness conductivity of the unmodified composites (CP) was 20 S/m. After introducing yarn into the system, the through-thickness conductivity was increased significantly. SC12.5 had a conductivity of around 2583 S/m, which was about 130 times higher than the CP. The conductive veil does not affect the through-thickness conductivity, as indicated by the similar through-thickness conductivity of SC12.5 and SC12.5CV. Similarly, for the SC5 and SC5CV samples, the through-thickness conductivity of the stitched composites with and without the conductive layer was in the same range. Hence, the through-thickness conductivity of the SC5 and SC5CV increased around 167 times from the CP. For the CP/Mesh, the through-thickness conductivity was lower than that of the CP due to two glass fibre veils integrated, on top and in between the carbon fibre and the mesh, which reduced the conductive paths from the top to the subsequent layers of the CP/Mesh sample.

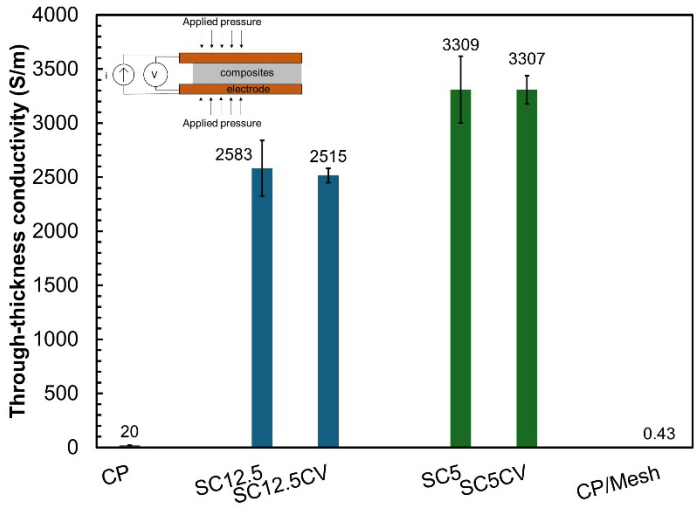


Figure 5 – Summary of the through-thickness conductivity of different types of samples.

3.2.2. High-voltage testing

High-voltage testing was used to evaluate the lightning-strike protection performance of the composites. The test setup is illustrated in Figure 6. The simulated high-voltage impulse was generated within microseconds. The generated impulse during the testing is shown in Figure 7.

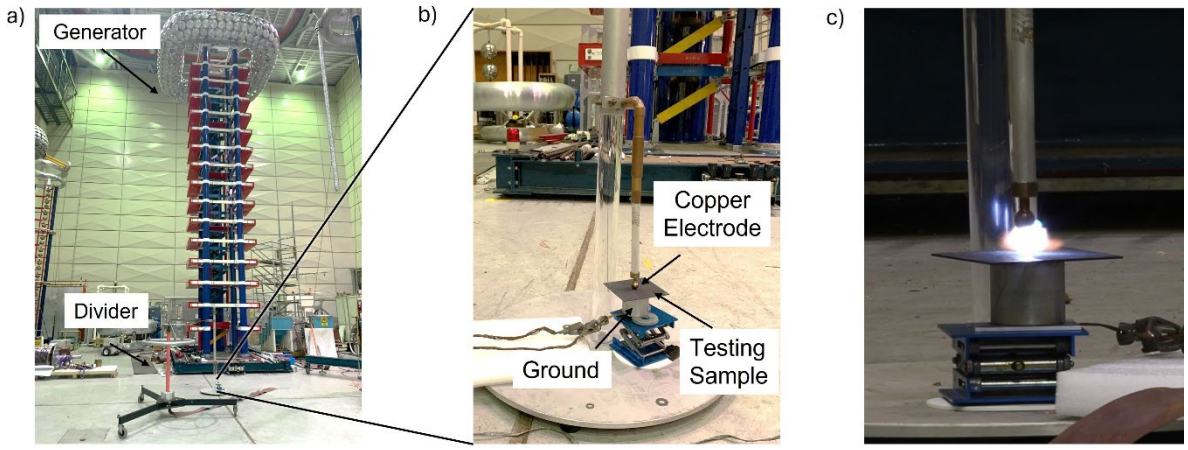


Figure 6 – (a) High-voltage testing at the NMI facility, (b) the test set-up for the high-voltage impulse testing, and (c) plasma generated during the high-voltage testing.

The surface damage of the composites after the high-voltage testing was investigated under the optical microscope, as shown in Figure 7. The damage region is indicated by the yellow dotted boundaries. The damage characteristics of the unmodified composites consisted of carbon fibre ablation (dark region) and resin embrittlement (white region) in Figure 7a. A similar type of damage characteristic can also be observed in the stitched composites. In addition, damage was detected on the conductive yarns. The darkened regions on the conductive yarn surfaces were attributed to yarn burning and metal vaporisation during the high-voltage impact. The SEM images (Figure 8) are also used to confirm the damage characteristics of the conductive yarn. The SEM images revealed that, after high-voltage exposure, the conductive yarns remained in contact with the composite surface even though part of the surrounding resin had been ablated. However, some parts of the silver-coated layer had been vaporised, leaving sections of the base yarn exposed. Furthermore, the conductive veil provides additional conductive paths and facilitates current flow to the adjacent stitching lines, as demonstrated in SC12.5CV (Figure 7c), where a reduced damage zone was observed on the composite surface, especially within the grid areas, compared to SC12.5 (Figure 7b). This suggests that although the damage might not be eliminated by integrating a conductive surface layer, this layer can direct current towards the conductive yarns, which is the primary protection mechanism.

The damage characteristic of the CP/Mesh is demonstrated in Figure 7f. The copper was vaporised at the impact location, exposing the bare carbon fibre composite surface underneath. This indicates that the glass fibre veil also ablated during the test. It has been reported that the non-conductive layer beneath the copper mesh can prevent current from lightning from passing through the subsequent layers [23]. The contradictory result may be attributed to the different generated lightning sources used. The typical lightning strike simulation is a high-current generator with a voltage usually less than 30 kV [24]. In this work, a high discharge voltage of 50 kV was employed. This indicates that the non-conductive layer underneath the copper mesh may not be sufficient for protection in the real scenario where the voltage can exceed 100 kV [24].

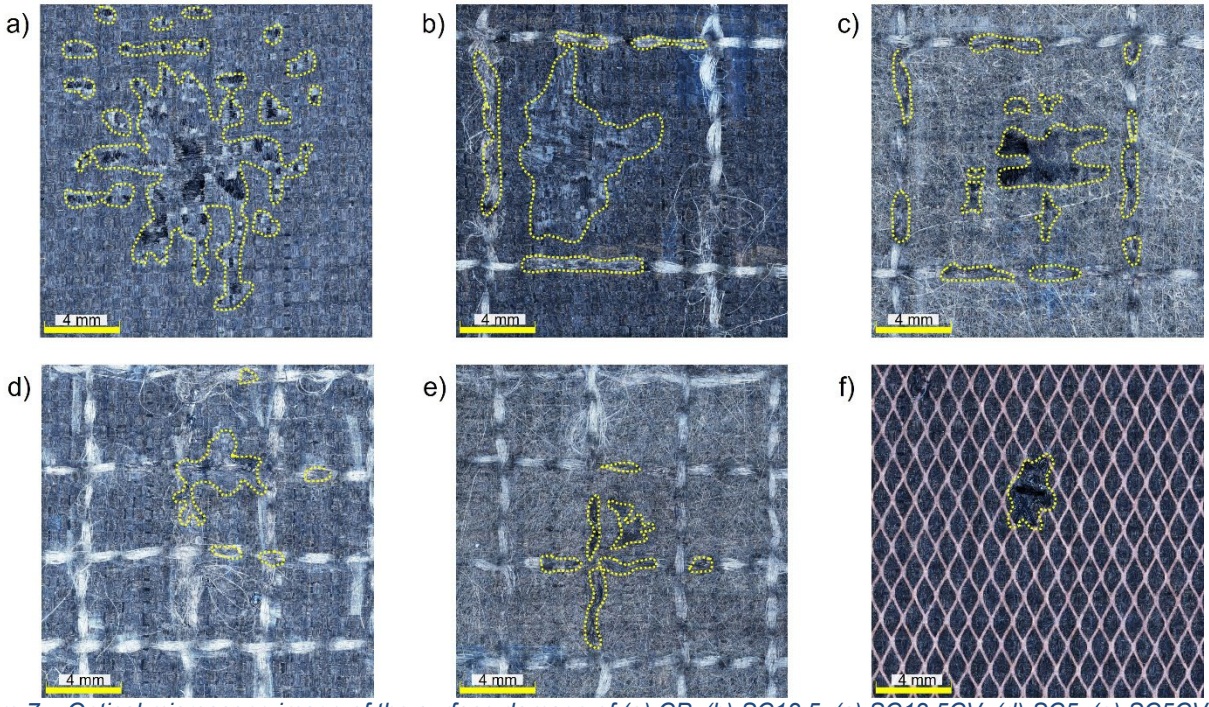


Figure 7 – Optical microscope image of the surface damage of (a) CP, (b) SC12.5, (c) SC12.5CV, (d) SC5, (e) SC5CV, (f) CP/Mesh.

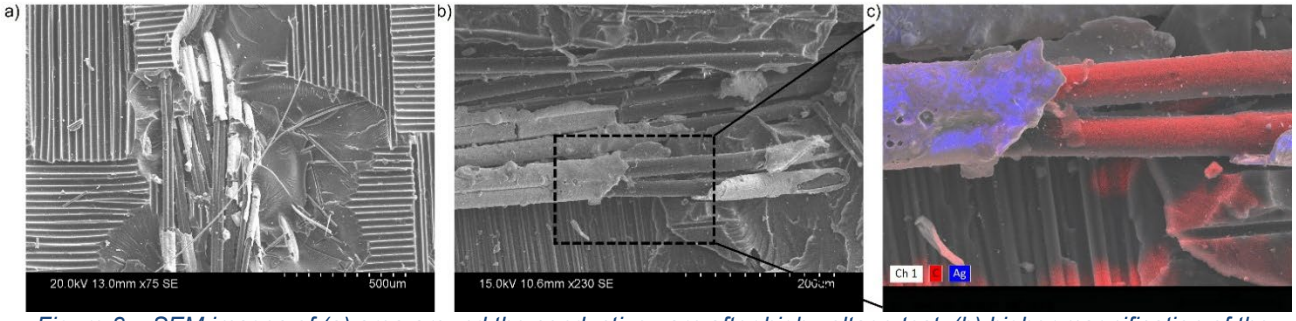


Figure 8 – SEM images of (a) area around the conductive yarn after high-voltage test, (b) higher magnification of the damaged yarn, and (c) EDS mapping of the yarn.

A summary of the surface damage area corresponding to the electrical conductivity is illustrated in Figure 9. The damage area of the unmodified composites (CP) was around 35.39 mm^2. The SC12.5 demonstrated a reduction in damage area of approximately 52.4% compared to the CP. With the conductive coating, the SC12.5CV showed a further reduction in the damage area, with a decrease of around 60.1% compared to the CP. The slight decrease in the damage area was due to the increase in the in-plane conductivity from the conductive veil. With the smaller grid size (SC5), the damage was further reduced to 6.71 mm^2, accounting for an 81.0% reduction when compared to the CP, while the SC5CV demonstrated a lower damage area, with an 83.8% reduction achieved. It can be seen that SC12.5CV benefited more significantly from the integration of the conductive veil compared to SC5CV. This behaviour can be attributed to the already high electrical conductivity of SC5, resulting in a comparatively smaller contribution from the conductive veil in SC5CV. In addition, the larger open area within the stitching grid of SC12.5V allowed the conductive veil to play a greater role in facilitating current transfer towards the integrated conductive yarns.

The surface damage area of the CP/Mesh was around 4.77 mm^2, which was around 86.5% reduction from the unmodified composites. Although it demonstrated the largest surface area damage reduction, the statistical t-test demonstrated that there is no significant difference in the damage surface area between the CP/Mesh and SC5 and SC5CV. This indicates that the stitched composites have potential as an alternative lightning strike protection approach. However, the risk of mechanical performance reduction due to high stitch density necessitates investigation.

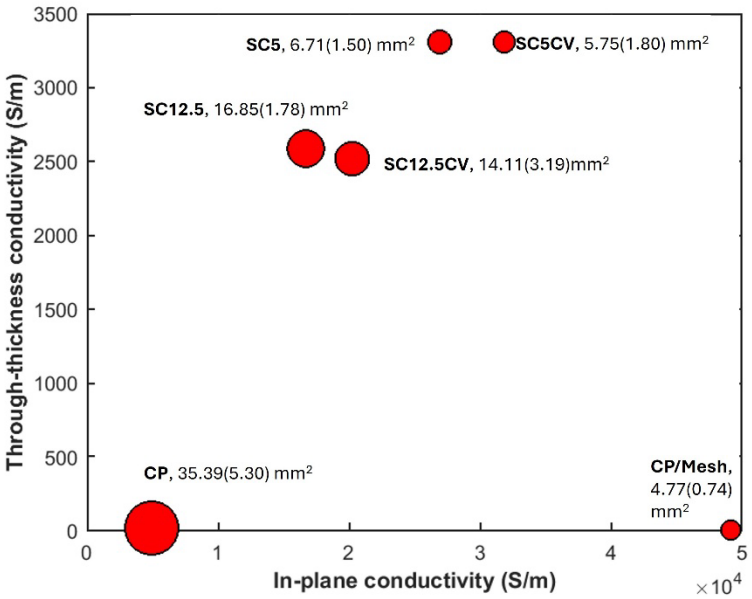


Figure 9 – Plot summarising surface damage area (standard deviation indicated in the parentheses) with corresponding through-thickness and in-plane conductivity in the longitudinal direction.

3.2.3. Flexural Properties

The flexural properties were used to study the mechanical performance of the fabricated composites before and after the high-voltage test. The summary of the flexural strength and modulus before the high-voltage test is summarised in Figure 10a. The flexural strength of the unmodified composite (CP) was 728 MPa. All modified composites recorded lower flexural strengths compared to the CP. Introducing yarn into the system lowered the strength value by around 17% for SC12.5. This reduction is mainly due to the fibre misalignment and resin-rich areas inducing stress concentrations from the stitches [25, 26]. After adding the conductive veil, the SC12.5CV exhibited a similar strength reduction to SC12.5, with around 18% decrease from the CP. Interestingly, the CP/Mesh also exhibited similar flexural strength to SC12.5 and SC12.5CV. This strength reduction is primarily due to the lower carbon fibre volume fraction compared to the CP from the addition of the non-structural layers, including the copper mesh and two glass fibre veils. This indicates that the SC12.5 and SC12.5CV still maintain sufficient strength compared to the composites with a regular setup for the lightning strike protection structure. However, at a low grid size or SC5, the flexural strength reduced further to 35% reduction from the CP. This pronounced reduction is mainly attributed to increased fibre misalignment and reduced fibre volume fraction of SC5. When adding the conductive veil, SC5CV demonstrated higher flexural strength with 29% reduction compared to the CP. This higher strength of SC5CV mainly comes from the failure location. All SC5 specimens fractured at the yarn locations, which led to lower strength compared to SC5CV, where some specimens experienced failure away from the perpendicular stitching line, lessening the impact from stitching.

The flexural modulus of the CP before the high-voltage testing was 45.5 GPa, while all the modified composites also demonstrated a lower modulus. At SC12.5, the modulus was 39.5 GPa, which was around 13.2% reduction from the CP. When adding the conductive layer, the modulus slightly decreased to 38.2 GPa, or an 18% decrease from the CP. At a smaller grid size, the modulus was further reduced to 33.1 and 32.5 GPa for SC5 and SC5CV, respectively. Similar to flexural strength, the reduction in modulus mainly comes from the fibre misalignment and the local resin-rich regions at the stitch locations [27]. Furthermore, both of the stitched samples with conductive veils demonstrate lower moduli than their counterparts, suggesting that the coating layer is more compliant. The modulus of the CP/Mesh was found to be around 33.6 GPa, a 26% reduction from the CP, mainly due to the addition of non-structural plies, which reduced the fibre volume fraction.

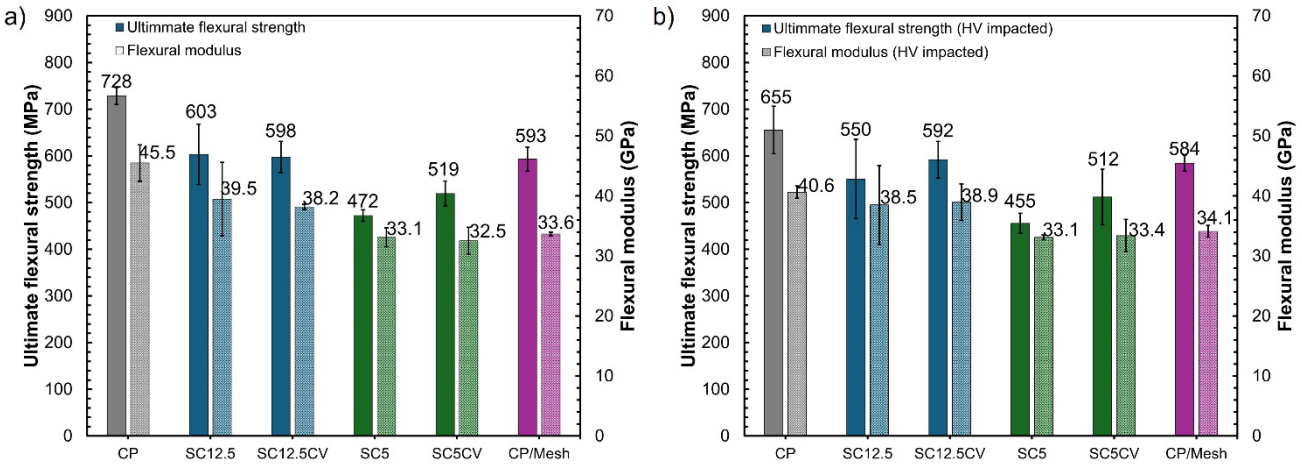


Figure 10 – Flexural strength and modulus test results of all composites: (a) before, and (b) after the high-voltage test.

The flexural strength and modulus after the high-voltage impact is summarised in Figure 10b. Since the high-voltage damage does not penetrate deeply into the laminate, the strength reduction is not substantial. However, the result can still provide a useful trend for the performance of the high-voltage protection across all samples. Table 2 summarises the strength and modulus retention after the high-voltage test. It can be seen that the baseline composites experienced an approximately 10% reduction in flexural strength after the impact, while the CP/Mesh, or the traditional lightning strike protection, retained 98.5% of the strength before the impact.

Table 2 – Flexural strength and modulus retention of each sample types.

Sample	Strength retention (%)	Modulus retention (%)
CP	90.0	89.3
SC12.5	91.2	97.5
SC12.5CV	99.0	102.0
SC5	96.5	99.9
SC5CV	98.6	102.7
CP/Mesh	98.5	101.4

For the stitched composites, the SC12.5 provided a slight improvement, with an 8.8% strength reduction compared to the SC12.5 before high-voltage impact. Both surface damage quantification and the strength investigation indicate that the conductive yarn is beneficial for high-voltage protection. Notably, with the conductive veil integration, the strength of SC12.5CV was retained at 99% of the value achieved from its non-impacted counterparts. The optical microscope image (Figure 7c) shows that the damage area in SC12.5CV is more concentrated on the conductive yarn. With the SC5 and SC5CV specimens, the flexural strengths were around 455 MPa and 512 MPa, corresponding to 96.5% and 98.6% retention, respectively. All SC12.5CV, SC5, and SC5CV have higher strength retention than SC12.5. This suggests that the damage being primarily concentrated at the conductive yarns can effectively protect the structural composites against high-voltage impulses. Additionally, having the conductive veil can enhance the protection by transferring the resulting current to the conductive yarns as the main protection mechanism.

Another interesting point is that the SC12.5CV provides a similar strength retention compared to the CP/Mesh, although the surface damage area was larger. This can be attributed to the damage characteristic of CP/Mesh, where the damage depth of CP/Mesh was around 0.02 mm deeper than SC12.5CV. This aligns with previously reported that the strength retention depends on both damage area and depth [15].

From the flexural strength results before and after the high-voltage test, SC12.5CV demonstrates a high potential as an alternative lightning strike protection material that demonstrates the most balanced electrical and mechanical performance. It showed a similar strength level compared to the traditional copper mesh samples before and after the high-voltage impact. Hence, it will be beneficial to continue investigating these fabricated composites under high-current conditions to fully

investigate the potential of using this in real-life applications.

4. Conclusion

A novel approach to developing highly conductive structural composites while maintaining sufficient mechanical performance was successfully demonstrated by integrating soft conductive stitching with a silver-coated conductive carbon fibre veil. The optimal coating thickness of the conductive veil was first determined to be 300 nm. After integration into the stitched composites, the conductive veil improved the in-plane electrical conductivity by approximately 25% compared to the stitched composites without the veil.

Among all stitched composites, the stitched composites with a 5 mm grid size integrated with the conductive veil exhibited the highest in-plane electrical conductivity. Although the conductive veil has minimal influence on the through-thickness conductivity, both the 5 mm stitched composites with and without the conductive veil demonstrated the highest through-thickness conductivity enhancement, reaching approximately 167 times greater than the baseline composites. However, the mechanical performance of the 5 mm grid size composites was less favourable due to the higher stitching density, which led to increased fibre misalignment.

Interestingly, despite the lower stitching density, the composites with a 12.5 mm grid size integrated with the conductive veil exhibited flexural strength comparable to those protected with commercial copper mesh, both before and after high-voltage impact testing. This behaviour was mainly attributed to the efficient transfer of electrical impulses to adjacent conductive yarns, which served as the primary pathways for current dissipation. The results highlight the advantages of combining conductive stitching with a silver-coated conductive veil over conventional lightning strike protection materials, including reduced risk of galvanic corrosion, improvement in delamination resistance, and the ability to maintain the structural integrity of the composites.

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