



Short Communication

Flexural and low velocity impact behaviour of hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates

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ABSTRACT

Recently, there has been an increasing interest in the development of innovative fibre metal laminates with significantly enhanced flexural strength and impact resistance. The objective of this study is to develop stainless-steel wire mesh/carbon-fibre reinforced epoxy laminates and examine their flexural and low velocity impact behaviour as a function of steel wire mesh reinforcement. The damage caused by low velocity impact was examined using optical microscopy and micro computed tomography (micro-CT). Steel wire mesh reinforcement increased low velocity impact performance because of its ductility, which dissipates energy across the cross-section and enables the structure to absorb more energy than an unreinforced composite. Scanning electron microscopy images of the composites' cross-sectional microstructure showed the carbon fibres and steel wires' wettability, indicating a strong reinforcement-epoxy matrix interface. Steel wire mesh reduced fragmentation and delamination damage in the impact cone and helped retain composite structural integrity, according to micro-CT data. However, the influence of steel mesh reinforcement on flexural behaviour was insignificant. In conclusion, the developed hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates possess enhanced impact properties, which can make them promising candidates specifically for aerospace and defence applications.

1. Introduction

Carbon fibre and glass fibre reinforced polymers (GFRP and CFRP) have been extensively utilized in numerous industries, including aerospace, automotive, marine, and infrastructure [1,2]. Nonetheless, the mechanical properties of these composites (e.g., impact-resistance, flexural strength, and tensile strength) must be enhanced due to the growing demand, particularly in the aircraft industry [1]. Thus, fibre metal laminates (FMLs) were introduced about 40 years ago, in which thin metals (mainly aluminium sheets) are inserted between the composite plies [3]. Over the last decade, interest in developing new FMLs with increased flexural strength and impact resistance has grown. Consequently, metal wire mesh reinforced GFRP [2] and CFRP [1] hybrid composites have been produced recently. To date, the limited literature has demonstrated that metal wire mesh reinforced composites possess considerable mechanical properties (i.e., low-velocity impact resistance, tensile, and flexural properties) [1,2,4-7].

Sakthivel et al. [7,8] demonstrated that adding steel wire mesh to GFRP improves its tensile, flexural, and impact properties, which was attributed to the increased load bearing capacity and restrained micro-crack propagation with steel wire mesh reinforcement [7,8]. In another study [6], the addition of aluminium wire mesh layers increased the toughness of glass fibre reinforced epoxy matrix composites under tensile and flexural loading at the expense of tensile and flexural strength. Similarly, Sadoun et al. [5] demonstrated that the addition of aluminium mesh improved the ductility of the glass fibre reinforced epoxy composites with a compromise in tensile and flexural strength, which was attributed to the intrinsic ductility of Al in comparison to glass fibre [5]. A recent study [2] demonstrated that steel wire mesh addition could improve the impact-resistance capacity of GFRP by dispersing the incident energy from the impact centre to the outer region. In a recent study, Wan et al. [1] revealed that the low-velocity impact resistance of stainless steel and aluminium wire mesh incorporated carbon fibre reinforced/epoxy laminates produced by hot pressing

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was greater than that of pure carbon fibre reinforced/epoxy laminates, which was attributed to the ductility of metal wire mesh, absorbing and transferring more impact energy. The aforementioned literature gives unique insight into the incorporation of metal wire mesh into GFRP and CFRP composites, but further study is required to improve our understanding in the field.

To the authors' knowledge, the present study is the first to investigate both the flexural and low-velocity impact performance of stainless-steel wire mesh/carbon fibre reinforced composites manufactured using vacuum assisted resin transfer moulding (VARTM). The three-point bending, four-point bending, and low-velocity impact properties of the hybrid stainless steel wire mesh/carbon-fibre reinforced epoxy laminates were examined in detail as a function of the addition of wire mesh. Optical microscopy and X-ray computed tomography (XCT) were used to characterize and compare the damage mechanisms of composites following low-velocity impact tests. The wettability of the fibres and the interface between the matrix and fibres were observed through the analysis of cross-sectional SEM images of the composites.

2. Materials and methods

The present study involves the processing of hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates by VARTM and the

analysis of the flexural and low-velocity impact behaviour of the processed composites (Fig. 1).

2.1. Materials

As the matrix material, Araldite LY 8601 resin was used; its physical and mechanical properties are listed in (Table 1). The matrix material was combined with Aradur 8602 hardener at 25 wt %. As the fibre material, Airtech ST-12K-T480 carbon fibre was selected, which consists of 12,000 fibre strands per knit bundle and is knitted in 0-90° directions with a density of 3 knits per 1 cm. AISI 304 steel wire mesh with 100 mesh density (i.e., 0.154 mm mesh spacing) and 0.1 mm wire thickness was employed to strengthen the composite.

Table 1
Physical and mechanical properties of matrix material (Araldite®LY8601).

Properties	ASTM Standard	Test values
Density (gr/cm ³)	D-792	1.12
Hardness (Shore D)	D-2240	82
Tensile strength (MPa)	D-638	54.3
Compressive strength (MPa)	D-695	106.18
Elongation at break (%)	D-638	6

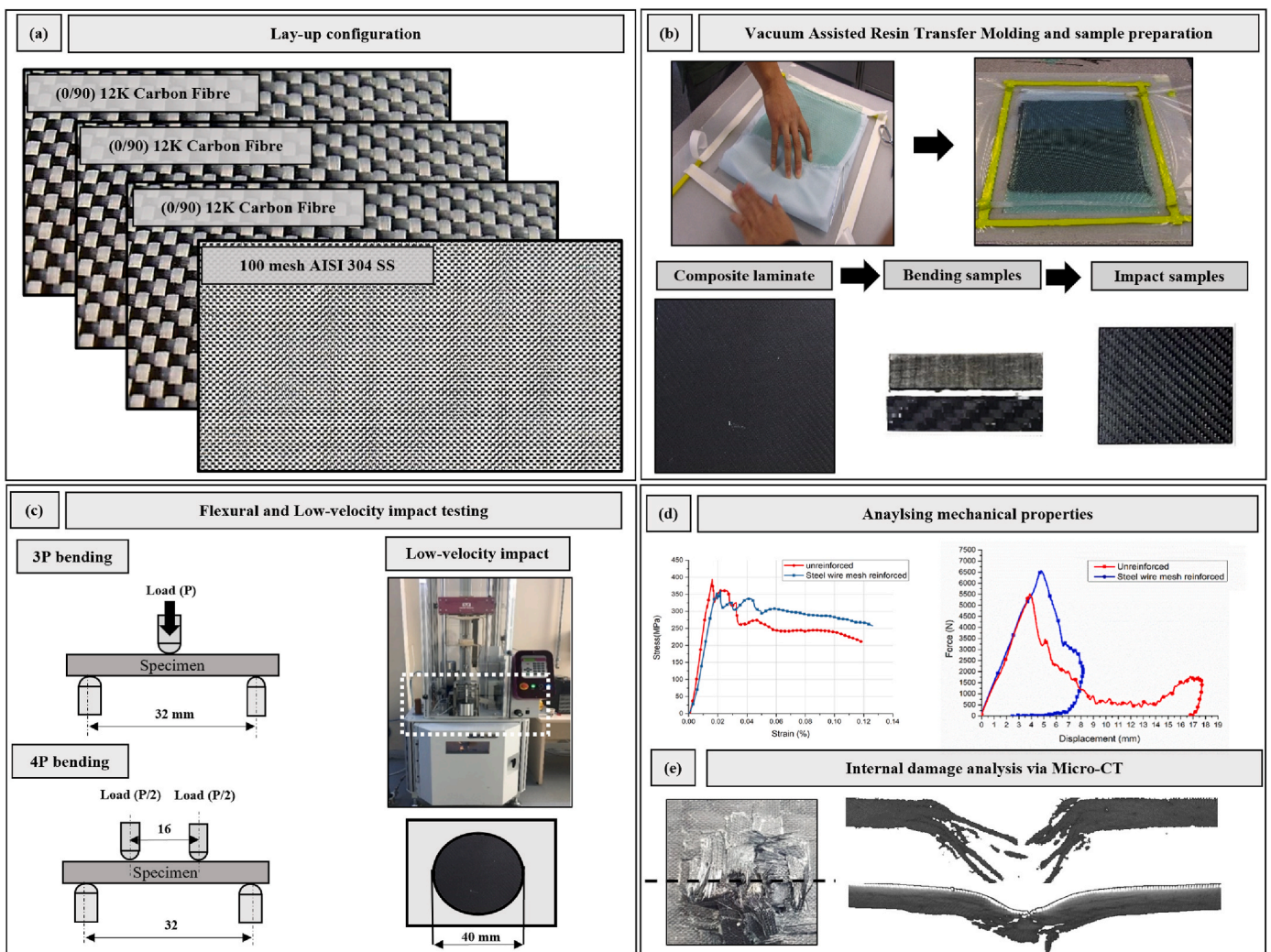


Fig. 1. Flow chart, key processing, and experimental parameters of the present study: (a) lay-up configuration of hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates, (b) processing of the composites and sample preparation, (c) flexural and low-velocity impact testing of the composites, (d) analysing mechanical properties, and (e) damage analysis of impacted composite samples via optical microscopy and X-ray CT.

2.2. Processing of laminates

Carbon-fibre reinforced epoxy and hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates were produced by VARTM. The carbon-fibre reinforced epoxy consists of three layers of carbon fibre fabrics in the same direction [0/90], whereas the hybrid metal wire mesh/carbon-fibre reinforced epoxy laminates have a steel wire mesh on the surface (Fig. 1-a). The resin-hardener mixture was injected into the layers of the composite to accomplish wetting, and then the composites were cured at room temperature for 12 h under vacuum (Fig. 1-b). The composite laminates were removed by properly pulling off the mould and cleaned by cutting the lining fabric and excess materials. Finally, rectangular steel wire mesh reinforced and unreinforced carbon-fibre/epoxy composite laminates (300 mm × 250 mm × 2 mm) were manufactured. Using an abrasive water jet cutter, the manufactured laminates were then cut to the proper dimensions for 3-point bending tests (12.7 mm × 50 mm × 2mm per ASTM D 6272), 4-point bending tests (12.7 mm × 50 mm × 2mm per ASTM D 6272), and low velocity impact testing (100 mm × 100 mm × 2mm per ASTM D 7136). Finally, the cross-sectional microstructure of the composites was subsequently analysed using a scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) detector, as detailed in the supplementary material.

2.3. Flexural testing

In accordance with ASTM D 6272, three-point (3-P) and four-point (4-P) bending tests were carried out at a crosshead speed of 2 mm/min at room temperature using an Instron 4411 tensile tester. The experimental setup for 3-P and 4-P bending tests is schematically depicted in Fig. 1-c. The bending tests were performed in five replicates for both unreinforced and steel wire mesh reinforced composites.

2.4. Low velocity impact testing

In accordance with ASTM D7136, low-velocity impact tests at an incident energy of 50 J were carried out using a drop-weight impact device (Instron 9350). In impact testing, both the contact force and displacement data of the impactor with a tip diameter of 10 mm and a total mass of 9.3 kg were collected with a 4 MHz data acquisition frequency. The data were then analysed with VisualIMPACT software, which allowed force measurements to be processed as a function of time and specimen deformation. The impact tests were performed in three replicates for both unreinforced and steel wire mesh reinforced composites.

2.5. Damage assessment

After low-velocity impact tests, visual and internal damage investigations were performed via optical microscopy and X-ray computed tomography (XCT). To examine the internal damage mechanisms of the composite laminates, XCT images were acquired from a 25 mm wide and 70 mm long region surrounding the impact damage with a 2D spatial resolution of 10 μm using an XCT scanner (SCANCO MEDICAL μCT 50). XCT image analysis was performed using ImageJ® software to reveal the damage mechanisms concentrated at the impact damage cone.

3. Results and discussions

3.1. Flexural properties

Steel wire mesh slightly enhances composite flexural strength under 4-P bending but diminishes strength under 3-P bending (Fig. 2). However, adding steel wire mesh dramatically improves the composite's toughness (area under the stress-strain curve), increasing its energy absorption capacity. Sadoun et al. [5] reported that the flexural strength of GFRP composites decreases with aluminium wire mesh addition due to the relatively poor bonding strength between the aluminium mesh and the epoxy matrix, while the ductility improves due to the inherent ductility of aluminium mesh. Similar results were demonstrated by Megahed et al. [6] as the flexural strength of GFRP composites decreased when reinforced with aluminium mesh, while ductility increased dramatically. In contrast, a slight increase in flexural strength was observed for GFRP composites with steel wire mesh reinforcement [8]. Recent studies reported that the incorporation of steel wire mesh reinforcement into GFRP [9] and CFRP [10] composites slightly increased their flexural strength. To enhance the strengthening efficacy of the composites, it is recommended that the surfaces of steel wire mesh and glass fibre be treated [9]. It is also concluded that since wire mesh sheets are perforated, they integrate mesh steel with carbon fibre and penetrate the epoxy matrix, making them a good alternative to fibre metal laminates (FMLs) [10]. Recently, a study found that CFRP tensile behaviour depends on the type of reinforced stainless steel wire mesh (coarse, moderate, and fine) into the polymer matrix [11].

In conclusion, the limited literature demonstrates conflicting findings on the effect of metal wire mesh reinforcement on flexural strength, while both aluminium and steel wire mesh reinforcement improved composite ductility (strain at break and toughness). In the present study, the effect of steel wire mesh on flexural strength is negligible, whereas it increases the toughness of CFRP composites.

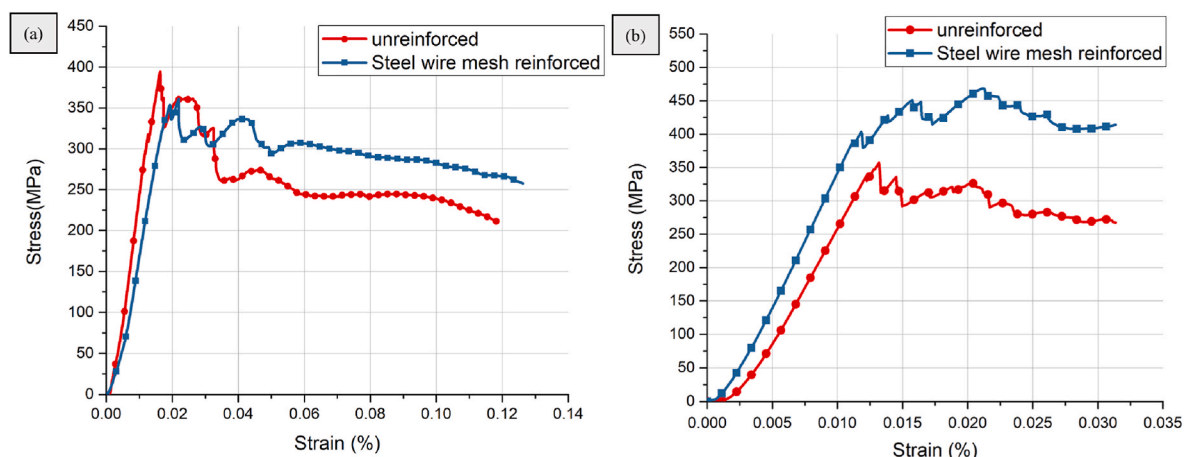


Fig. 2. Stress-strain curves of unreinforced and steel wire mesh reinforced composites under 3P (a) and 4P (b) bending.

3.2. Low velocity impact properties

In Fig. 3, the force-time and force-displacement characteristics of unreinforced and steel wire mesh reinforced composites at the same impact energy differ significantly (50 J). The unreinforced and steel wire mesh reinforced composites reach peak contact forces of 5.5 kN and 6.5 kN within 1.5 and 2 ms, respectively. After attaining the maximum contact force, the unreinforced composite's contact force diminishes abruptly at 4 ms. Then, the contact force increases linearly to 12.5 ms and then falls to zero at 16 ms. For the steel wire mesh reinforced composite, the contact force drops rapidly up to 3 ms after achieving the maximum contact force, while the rebound energy region between 6 and 11 ms (8.3–5 mm) is significant. Fig. 3 c shows that the wire mesh reinforced composite can absorb more energy until peak force compared to unreinforced composite, indicating that steel wire mesh addition is effective in delaying the initial damage formation by transmitting the impact damage to a larger region within the structure [1,2], which was attributed to the ductility of metal wire mesh that can absorb the impact energy [1]. Thus, steel wire mesh reinforcement increases energy dissipation and improves the low-velocity impact performance of the CFRP composite. Thus, it is clear that steel wire mesh reinforcement increases energy dissipation and improves the low-velocity impact performance of the CFRP composite.

As recent literature reported, the interface between the metal wire-reinforced polymer layers strongly influences the mechanical response of hybrid composites [1,4,6,12]. Supplementary Figure 1 and Fig. 2 provide detailed SEM images and EDS analysis to reveal the wettability of reinforced fibres and steel wire mesh. The SEM image (Supplementary Fig. 1) showed epoxy-covered carbon fibres with visible matrix

adhesion, indicating adequate fibre/matrix adhesion during curing [13]. Similar matrix coverage was also visible for the steel wire mesh (Supplementary Fig. 2), revealing the wettability of the steel wire mesh and the strong interface between the matrix and steel wires.

3.3. Damage assessment

Fig. 4 shows the internal damage mechanisms of unreinforced and steel wire mesh reinforced composites following low velocity drop testing. XCT analysis shows total perforation in the unreinforced composite (Fig. 4-a), whereas the impact cone of the steel wire mesh reinforced composite sample still shows limited integrity (Fig. 4-b), complementing the previously discussed force-displacement curves of the respective samples (Fig. 3-b). XCT analysis reveals that delamination damage primarily concentrated in the impact cone is predominant for both composites [14]. However, fibre fracture and fibre/matrix pull out mechanisms are also prevalent for the unreinforced composite (Fig. 4-a), whereas steel wire mesh enhances energy and damage absorption since these mechanisms are somewhat limited for the steel wire mesh reinforced sample (Fig. 4-b). Wan et al. [1] have recently reported similar results, indicating the ductility of metal wire mesh improves energy absorption and transfers impact energy to the outer of the impact cone during the impact. In another recent study, adding steel wire mesh to GFRP resulted in a larger damage area, showing the transfer of damage due to the addition of steel wire mesh [2]. It is evident from the XCT analysis that steel wire mesh considerably lowers internal damage within the impact cone and assists in maintaining the integrity of the composite structure. To the authors' knowledge, the internal damage of low velocity impacted steel wire mesh reinforced CFRP composites has

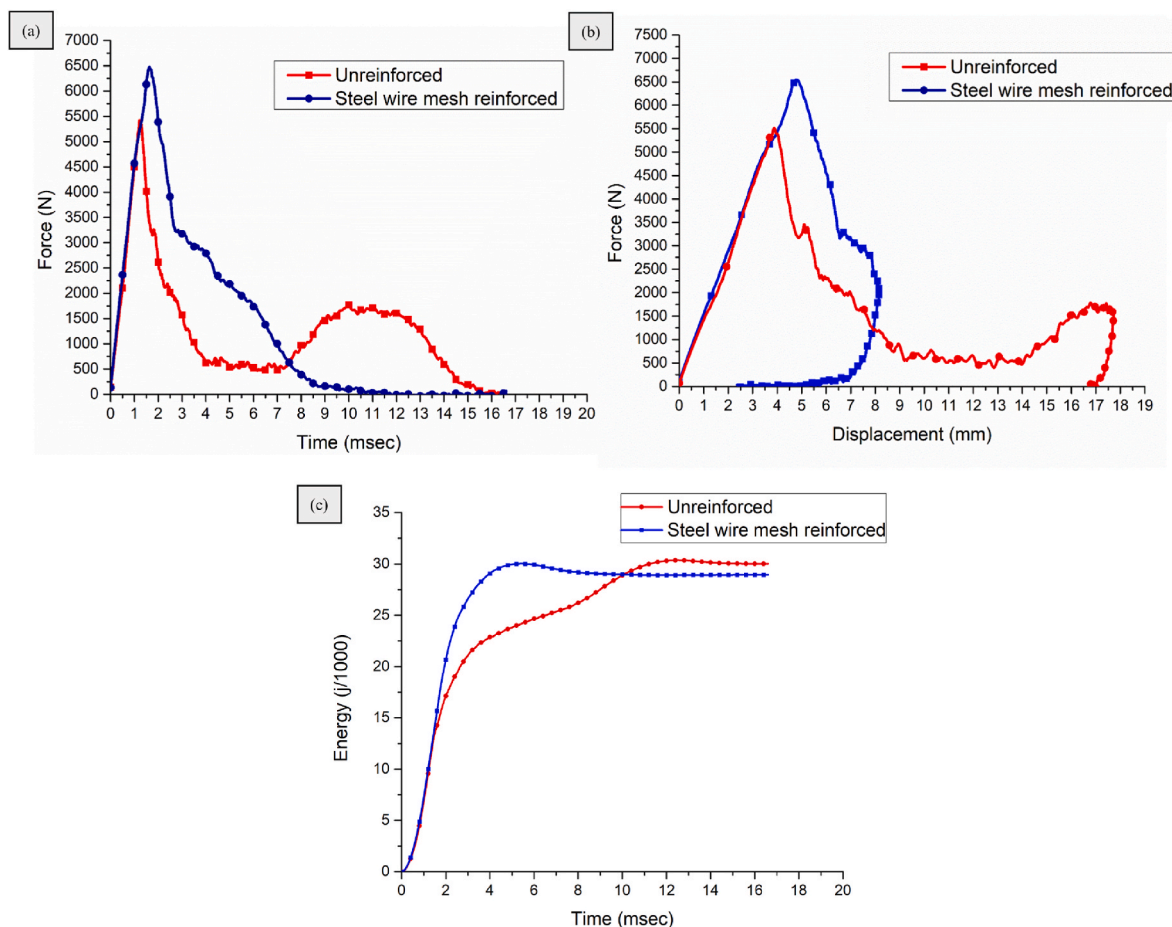


Fig. 3. Force-time (a), Force-displacement (b), and Energy-time curves of unreinforced and steel wire mesh reinforced composite samples under low velocity drop testing.

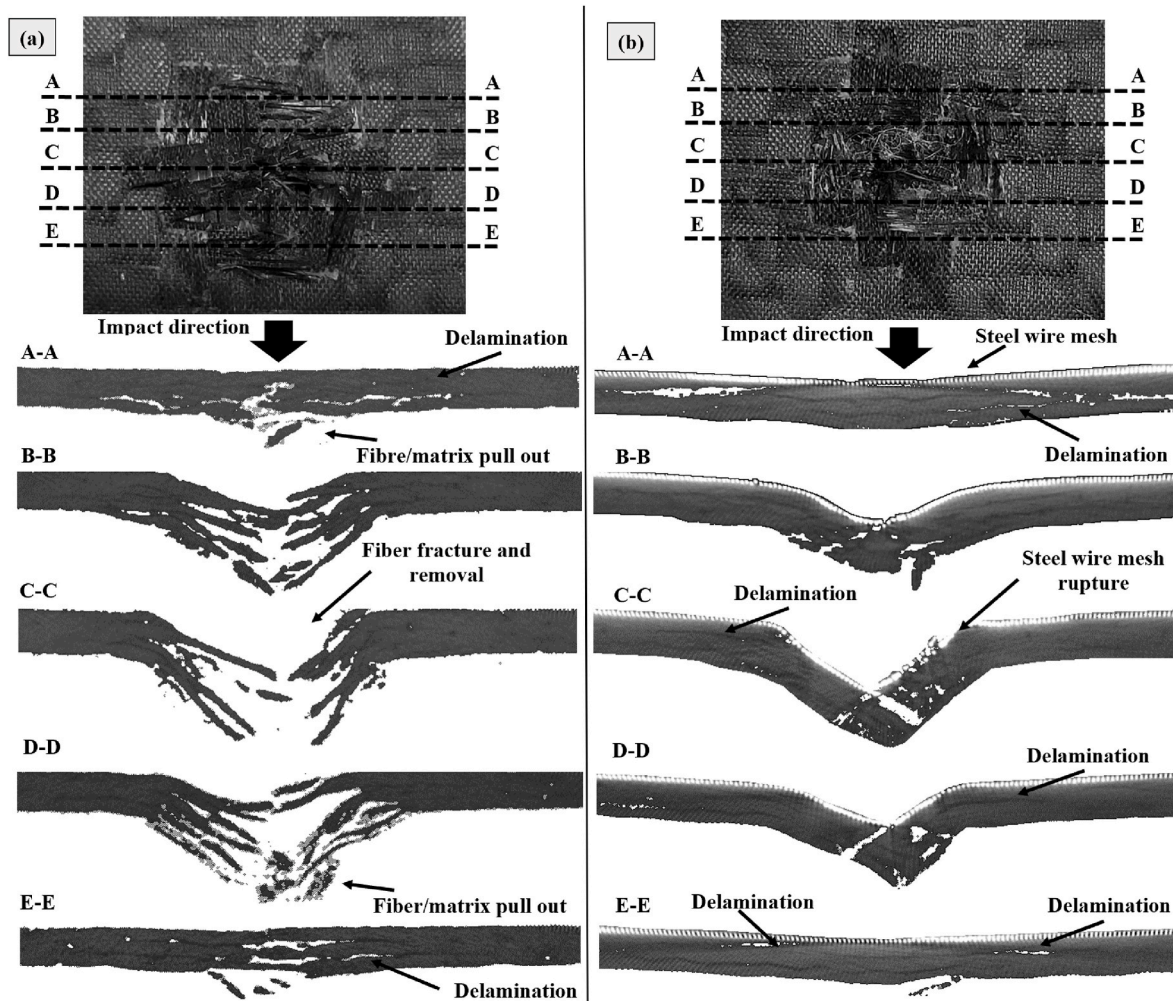


Fig. 4. XCT image analysis of impact damage cone of (a) unreinforced and (b) steel wire mesh reinforced composite samples following low velocity drop testing, revealing the damage mechanisms; damage mechanisms are highlighted by arrows and remarks.

been revealed for the first time.

4. Conclusions

For the first time, this study has revealed the low velocity impact behaviour and flexural properties of stainless-steel wire mesh/carbon fibre reinforced composites manufactured using VARTM. The internal damage of impacted composites has been revealed for the first time through XCT analysis. Steel wire mesh reinforcement significantly improves the low velocity impact performance of the composites, which is attributed to the ductility of the steel wire mesh that can dissipate the energy throughout the cross-section and allows the structure to absorb more energy compared to that of unreinforced CFRP. The XCT results support this hypothesis since adding steel wire mesh considerably lowers internal damage within the impact cone and assists in maintaining the integrity of the composite structure. Steel wire mesh increases toughness but has no effect on flexural strength. Future low-velocity impact tests with lower incident energies (less than 50 J) are suggested for the purpose of investigating the elastic recovery of composites. Future work should also include inter-laminar shear or pull-out tests to study fibre, wire, and polymer matrix bonding. The findings will help develop novel composites using metal wire mesh reinforcements, making them safer and more adaptable for low-velocity impact resistance applications like commercial airplane structural applications.

CRediT authorship contribution statement

Abdulkadir Cengiz: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.
İsmail Melih Yıldırım: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization.
Egemen Avcu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.coco.2024.101844>.

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