Research Article

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Experimental and numerical investigations on tensile properties of carbon fibre-reinforced plastic and self-reinforced polypropylene composites

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Abstract: This article aims to investigate the tensile properties of carbon fibre-reinforced plastic (CFRP) and self-reinforced polypropylene (SRPP) composites used in both experimental and numerical investigations. The experimental study evaluated the tensile strength, tensile strain, and modulus of CFRP and SRPP composite laminates under tensile loading. Finite element modelling was employed to predict and validate the tensile properties of these composites. CFRP and SRPP laminates were manufactured using the hot compression technique and stacked through the hand lay-up technique. The results revealed that CFRP with a unidirectional pattern provided a higher tensile strength (1,162 MPa) than the twill pattern (288 MPa) with nominal strain values of 0.017 and 0.013 in the CFRP-based system, respectively. It was observed that the results of CFRP and SRPP composites provided a good agreement between experimental and numerical investigations. Moreover, the failure behaviour of CFRP and SRPP laminates was evaluated and compared with experimental and numerical results. Furthermore, practical applications of CFRP and SRPP composites for lightweight parts are presented.

Keywords: tensile properties, carbon fibre-reinforced plastic, self-reinforced polypropylene

1 Introduction

Composites have increasingly become integral in advanced lightweight materials due to their benefits, such as a high strength-to-weight ratio, excellent strength properties, and high corrosion resistance [1]. Composites have attracted the interest of engineers and researchers, who have advanced their applications in diverse sectors, such as automotive [2], aerospace [3], civil construction [4], and sports equipment. The advanced composite materials are divided into fibre-reinforced composites, laminated composites [5], and matrix composites. Fibre-reinforced composite materials are characterized by high-strength fibres added to the continuous matrix, which included carbon fibres [5], glass fibres [6], aramid fibres [7], natural fibres [8], hybrid fibres, *etc.* The laminated composites are alternately stacked with various fibre laminates in a layer-by-layer fashion, which mainly laminated the fibres in different directions to control and exhibit their mechanical properties. The other composites are used for advanced applications in particular fields, such as shape memory [9], viscoelastic [10], and ceramic materials [11]. The ongoing exploration and enhancement strategies of advanced composite materials are further investigated in terms of structural reinforcement and potential applications.

Design strategies of fibre-reinforced composites are required to achieve higher strength properties and strength-to-weight ratios than traditional metals [12,13]. To improve the performance characteristics of advanced composites,

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many researchers have characterized the mechanical properties of fibre-reinforced composites with various fibre classifications [14]. For instance, Li *et al.* [15] investigated the effects of delamination defects on the mechanical properties of carbon fibre-reinforced plastic (CFRP) composites and concluded that the compression properties of CFRP are remarkably affected by the delamination area and depth. Sapuan *et al.* [16] presented the mechanical properties of longitudinal basalt/woven-glass-fibre-reinforced hybrid composites with hybridization strategies. They observed that adding basalt to the glass-fibre-reinforced unsaturated polyester resin increased its tensile and flexural properties. Ibrahim *et al.* [17] examined the effects of hybridization of interlayer composites on tensile and flexural properties and observed that the hybrid carbon/aramid fibre-reinforced plastic pointedly enhanced the flexural properties. In addition, Ismail *et al.* [18] discussed the effect of hybridization distribution on the mechanical properties of hybrid glass fibre/rice husk (RH)-reinforced polymer composites. The study showed that 5 wt% of RH fibre and 25 wt% of glass fibre exhibited the highest tensile, flexural, and impact strength. It was concluded that the hybridization strategy is an effective solution to enhance the mechanical properties of hybrid fibre-reinforced composites in substantial potential applications [19].

The mechanical characteristics of fibre-reinforced composites have been explored through experimental, numerical, and analytical approaches, providing diverse methods to predict the evaluation parameters. For example, Turjo *et al.* [20] examined the mechanical characteristics of natural fibre-reinforced composites through experimental and numerical approaches, which provide the solution in corrosive or humid environments. Moudood *et al.* [21] developed the geometric and displacement potential function approaches to predict the mechanical properties of flax fibre-reinforced epoxy composites, which had good conformity between the two approaches with practical applicability. Nematollahi *et al.* [22] adopted experimental and numerical methods to investigate the critical length of short Kenaf fibre-reinforced polypropylene (PP) composites, which can understand the interfacial loading transfer mechanism. Moreover, the failure behaviour of fibre-reinforced composites was mainly studied and validated between experimental and numerical approaches, which is helpful for understanding the failure mechanisms. For instance, Zhang *et al.* [23] investigated the 3D micromechanical failure of fibre-reinforced composites on damage initiation, propagation, and interaction on the micro-scale, predicting the complicated progressive failure mechanisms. Patel and Waas [24] presented an efficient two-scale model to predict the failure mode of tensile fracture in fibre-reinforced composites, which was in good agreement with the corresponding experimental data. Lancioni and Alessi [25] proposed the variational model to describe the failure mechanisms in the short fibre-reinforced composite subjected to tensile loading. In addition, Quanjin *et al.* [26] used the digital image correlation method to investigate the tensile properties of aluminium and glass fibre-reinforced matrix composites, which is a functional approach to predict the tensile properties.

Self-reinforced polypropylene (SRPP) is a recycling-friendly, lightweight, low-density thermoplastic composite with excellent stiffness, impact strength, and shock resistance [27]. It was manufactured by adhering a layer of unidirectional (UD) PP fibre to a layer of isotactic PP matrix [28]. The growing focus on sustainable and eco-friendly materials is boosting and driving the market demand and advancements of SRPP due to its favourable properties and cost-effectiveness [29]. Some researchers have explored the engineering characteristics and performance of SRPP for their multi-functional structures [3,30,31]. For instance, Ma and Rejab [32] investigated the energy-absorbing characteristics of two-dimensional periodic SRPP honeycomb sandwich panels, and it was found that failure behaviour was highly sensitive to the relative density of the core. With growing interest in bio-based or self-reinforced materials, SRPP represents an emerging class of composites where the matrix and fibres are made from the same polymer. It offers the potential for simplified recycling as a promising alternative for applications where cost savings, weight reduction, and recyclability are critical factors. Furthermore, a comparison between CFRP and SRPP can balance the performance, cost, weight, and sustainability for potential as alternatives. Although various studies have been conducted to understand the tensile properties of advanced polymer composites, there is limited work reported on the properties of SRPP compared to CFRP composites with twill (TW) and UD patterns.

This article aims to investigate the tensile properties of CFRP with TW and UD patterns, as well as SRPP composites. Experimental studies of tensile strength, tensile strain, and modulus of CFRP and SRPP composites were conducted, and there is a reasonable agreement between experimental and numerical results. Moreover, the failure behaviour of CFRP and SRPP laminates was determined by the tensile properties of carbon fibre-reinforced and self-reinforced types. In addition, practical applications of CFRP and SRPP composites for lightweight parts are presented.

2 Materials and methods

2.1 Materials

Two rolls of carbon fibre prepregs with TW and UD patterns were supplied by the ZAComposite Company, Malaysia, which were stored in the freezer at −20°C before the preparation procedure. Specifications of the two CFRP prepregs are summarized in Table 1, including the weave pattern, resin content, and tensile properties. SRPP is a thermoplastic polymer supplied by Curv® Composites, and it is made from highly molecularly oriented thermoplastic fibres that are woven and bonded into a matrix of the same polymer. Standard SRPP Curv® is a 100% thermoplastic polymer and does not contain any inorganic fibres. SRPP sheets can be formed into three-dimensional parts through a pressure thermoforming process. Specifications of SRPP are provided in Table 2.

2.2 Fabrication procedure

CFRP prepregs of TW and UD patterns were stacked using the hand lay-up process. For the stacking orientation, the TW pattern of CFRP prepregs was laminated following the warp and weft weave directions. The UD pattern of CFRP prepregs was stacked with 0° fibre orientation following the loading direction. The pneumatic hot press machine was set to 5 bar with 3°C/min (heat up) and 5°C/min (cool down). The CFRP laminates with TW and UD patterns were placed into two compression platens, which were heated to 130°C for 60 min for the TW pattern, 120°C for 60 min for the UD pattern, and 130°C for 5 min for the SRPP. Later, the CFRP laminates and SRPP specimens were cooled down to room temperature (around 25°C). Figure 1 illustrates the curing temperature of CFRP and SRPP composite laminates used in this study. Tensile specimens were prepared with two sizes of the bonding aluminium end-tabs (*e.g.*, 50 mm × 25 mm × 1 mm and 50 mm × 15 mm × 1 mm). The geometric dimensions were 250 mm × 25 mm × 1 mm with three plies for the TW pattern and 250 mm × 15 mm × 1 mm with four plies for the UD pattern. The SRPP specimen was cut into 250 mm × 25 mm × 1 mm. Figure 2 presents the image of CFRP with TW and UD patterns and SRPP composite laminates.

Table 1: Specifications of CFRP prepregs with TW and UD patterns

Specifications	CFRP-TW	CFRP-UD
Weave pattern	TW	UD
Resin content (% wt)	40–55	40–45
Yarn count	3K	3K
Fibre areal weight (gsm)	200	200
Thickness of one-ply cured (mm)	0.35	0.25
Curing temperature (°C)	130	130
Dwell time (min)	60	60
Tensile strength (MPa)	68–78	2,450
Tensile modulus (GPa)	3–4	125
Compressive strength (MPa)	1,470	1,570
In-plane shear strength (MPa)	125	98

Note: Carbon fibre-reinforced plastic prepreg with a TW pattern: CFRP-TW; carbon fibre-reinforced plastic prepreg with a UD pattern: CFRP-UD. The datasheet was provided by the ZAComposite Company, Malaysia.

Table 2: Specifications of SRPP used in this study

Specifications	SRPP
Density (kg/m^3)	920
Poisson ratio	0.2
Tensile modulus (MPa)	160
Elastic modulus (MPa)	2,900
Yield stress (MPa)	230
Plastic strain	0.17
Fracture strain	0.07
Compression strength (MPa)	2,600–2,900
Flexural strength (MPa)	70
Flexural modulus (MPa)	3,400–3,700

2.3 Experimental test

The tensile test was used to investigate the tensile properties of CFRP and SRPP composite laminates in this study.

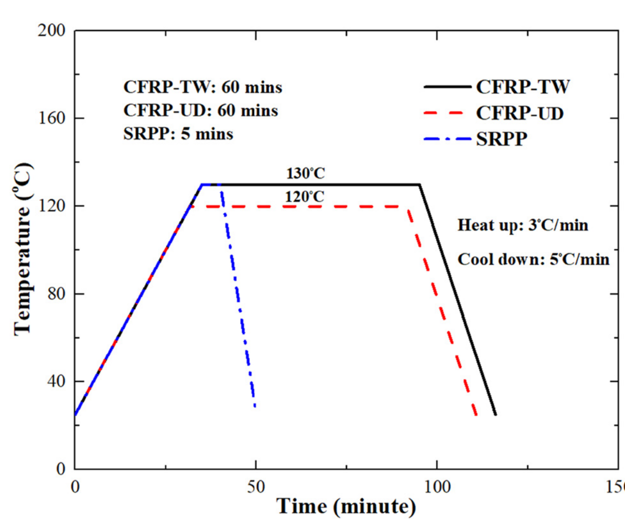

Figure 1: Curing procedure and temperature cycle of CFRP and SRPP composite laminates.

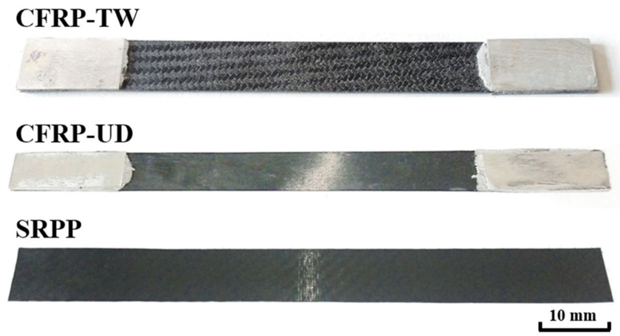

Figure 2: Photograph of CFRP and SRPP composite laminates used in this study.

The tensile test was conducted using the INSTRON 3369 universal testing machine, which had a maximum loading of 50 kN. The tensile test was set at 2 mm/min according to ASTM D3039 standards [33]. Figure 3 presents the experimental setup of CFRP and SRPP composites under tensile loading. A minimum of three specimens were performed under the tensile loading for each material. Tensile properties and failure behaviour of the CFRP and SRPP composite laminates, such as tensile strength, tensile strain, and modulus, were identified.

2.4 Finite element modelling

For the tensile part on CFRP and SRPP composite laminates, they have used the 3D solid deformable part. The CFRP composite laminates were stacked in three layers for a TW pattern and four layers for a UD pattern, which had a total thickness of 1 mm. Eight-node linear continuum components with reduced integration (C3D8R) and hourglass control were used to describe the tensile component. The

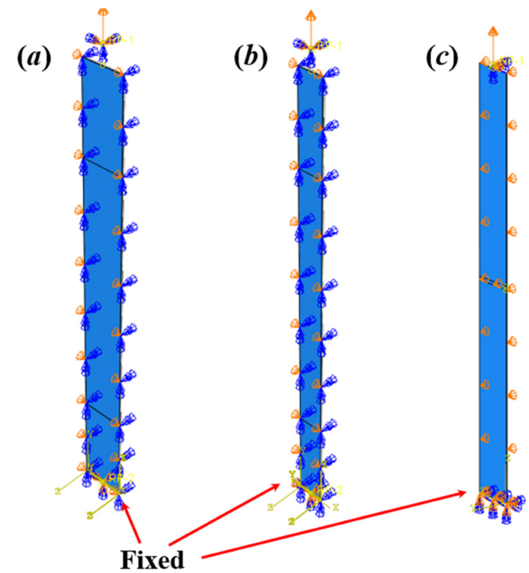

Figure 4: Modelling of boundary and loading conditions for composite laminates: (a) CFRP-TW, (b) CFRP-UD, and (c) SRPP.

boundary condition in the tensile test was clamped in the upper and lower fixtures. The lower fixture of the specimen was fixed in all directions, and the upper fixture was fixed in all directions but unconstrained in the longitudinal direction. Figure 4 illustrates the modelling of boundary and loading conditions for CFRP and SRPP composite laminates. The upper and lower aluminium end-tab position plates were set as the coupling constraint for the interaction condition. The reference point (RP-1) was created as the geometric centre of width and thickness. The degrees of freedom were all constrained in three direction displacements and rotations. Table 3 summarizes the modelling data on the mechanical properties of CFRP composites with two patterns. Table 4 lists the tensile stress *versus* strain data of SRPP material from the experimental test.

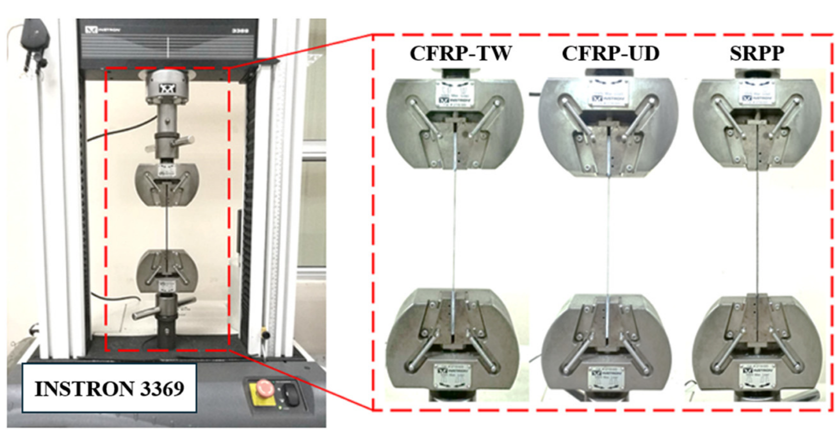

Figure 3: Experimental setup of CFRP and SRPP composite laminates under tensile loading.

Table 3: Modelling data on mechanical properties of CFRP composite materials with TW and UD patterns [34–36]

Mechanical properties	Symbol/unit	CFRP	
		TW pattern	UD pattern
Longitudinal tensile strength	X^T/MPa	280	1,250
Longitudinal compressive strength	X^C/MPa	180	1,000
Transverse tensile strength	Y^T/MPa	280	75
Transverse compressive strength	Y^C/MPa	180	220
Transverse tensile strength in thickness	Z^T/MPa	280*	75*
Transverse compressive strength in thickness	Z^C/MPa	30*	220*
Transverse shear strength	S^T/MPa	160	70
Longitudinal shear strength	S^L/MPa	160	70
Thickness shear strength	S^Z/MPa	120*	50*
Fracture energy in the longitudinal direction	G_{fx}/J	45*	100*
Fracture energy in the transverse direction	G_{fy}/J	45*	2*
Fracture energy in the thickness direction	G_{fz}/J	10*	2*

*Assumed values according to cited references.

The cohesive element model was used to simulate the delamination condition between layer to layer in composite laminates [34–36]. For the traction separation criterion, the constitutive relationship of cohesive elements idealizes the complex fracture mechanism issue. The mixed-mode linear energy-based damage propagation criterion was used, and the Benzeggagh–Kenane (BK) law was employed. The fracture energy G_c is given by

$$G_c = G_{Ic} + (G_{IIc} - G_c)\left(\frac{G_{shear}}{G_{Ic} + G_{shear}}\right)^{\eta}, \tag{1}$$

$$G_{shear} = G_{Ic} + G_{IIIc}, \tag{2}$$

where G_{IC}, G_{IIC}, and G_{IIIC} are mode I, mode II, and mode III fracture toughness, respectively, and η is the mixed-mode parameter.

Table 4: Tensile stress *versus* strain data of SRPP material

Engineering stress (MPa) [σ]	Engineering strain (ε)	True stress (MPa) [σ_t]	True strain (ε_t)	Plastic strain (ε_p)
28.5360	0.0300	29.3908	0.0295	0.0197
34.6320	0.0400	36.0157	0.0392	0.0272
40.6880	0.0500	42.7205	0.0487	0.0345
46.7920	0.0600	49.5974	0.0582	0.0417
52.8960	0.0700	56.5963	0.0676	0.0488
58.9520	0.0800	63.6654	0.0769	0.0557
65.0640	0.0900	70.9168	0.0861	0.0625
71.0960	0.1000	78.2023	0.0953	0.0692
77.0560	0.1100	85.5286	0.1043	0.0758
83.0640	0.1200	93.0279	0.1133	0.0823
88.8800	0.1300	100.4303	0.1222	0.0887
94.6720	0.1400	107.9217	0.1310	0.0950
100.3600	0.1500	115.4094	0.1397	0.1013
105.7280	0.1600	122.6396	0.1484	0.1075

The effective displacement δ_m was introduced, which considers the damage caused by the combined effects of normal and shear deformations. The damage variable of D_c was calculated during the linear degradation stage and is defined as follows:

$$\delta_m = \sqrt{(\delta_m)^2 + \delta_s^2 + \delta_t^2}, \tag{3}$$

$$D_c = \frac{\delta_m^f(\delta_m^{max} - \delta_m^0)}{\delta_m^{max}(\delta_m^f - \delta_m^0)}, \tag{4}$$

$$\delta_m^f = \frac{2G_c}{T_{eff}}, \tag{5}$$

where δ_m^f is the effective displacement at complete failure with T_{eff} as the adequate traction at damage initiation. δ_m^{max} refers to the maximum effective displacement attained. Some data on the cohesive layers were adopted from the literature [34–36].

3 Results and discussion

3.1 Results of CFRP and SRPP composites

The nominal stress *versus* nominal strain curves of the CFRP composite materials with TW and UD patterns are illustrated in Figure 5(a), which provides the tensile properties in the elastic deformation stage. Here, CFRP with TW and UD patterns showed a linear-shaped curve with a ductile response, in agreement with previous studies. The nominal stress was found to be sharply increased for both patterns based on the increasing strain value. CFRP

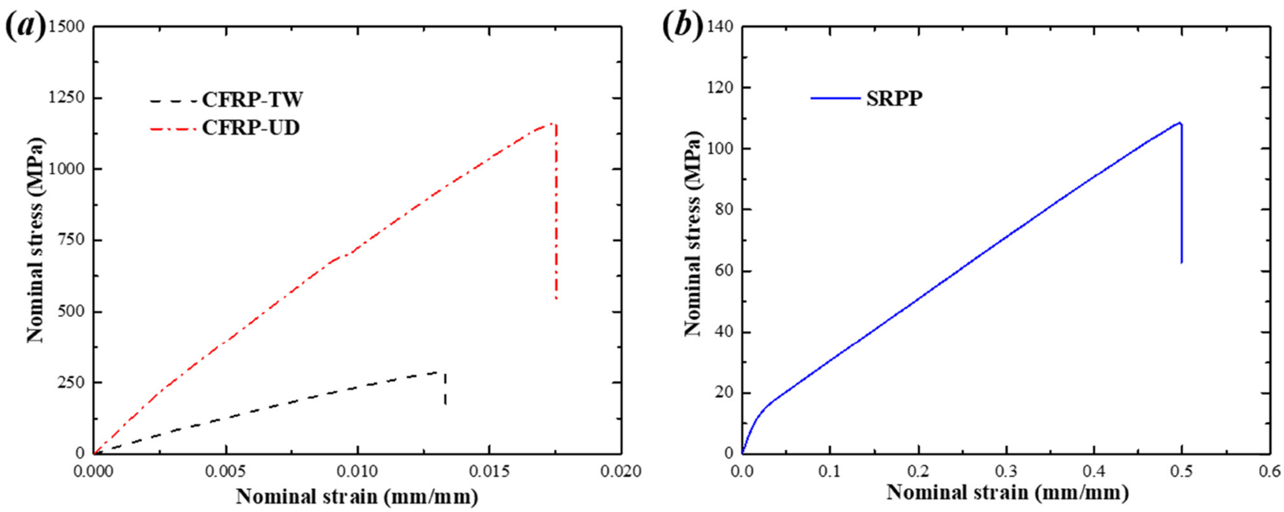

Figure 5: Nominal stress *versus* nominal strain curves of CFRP and SRPP composites: (a) CFRP-TW and CFRP-UD and (b) SRPP.

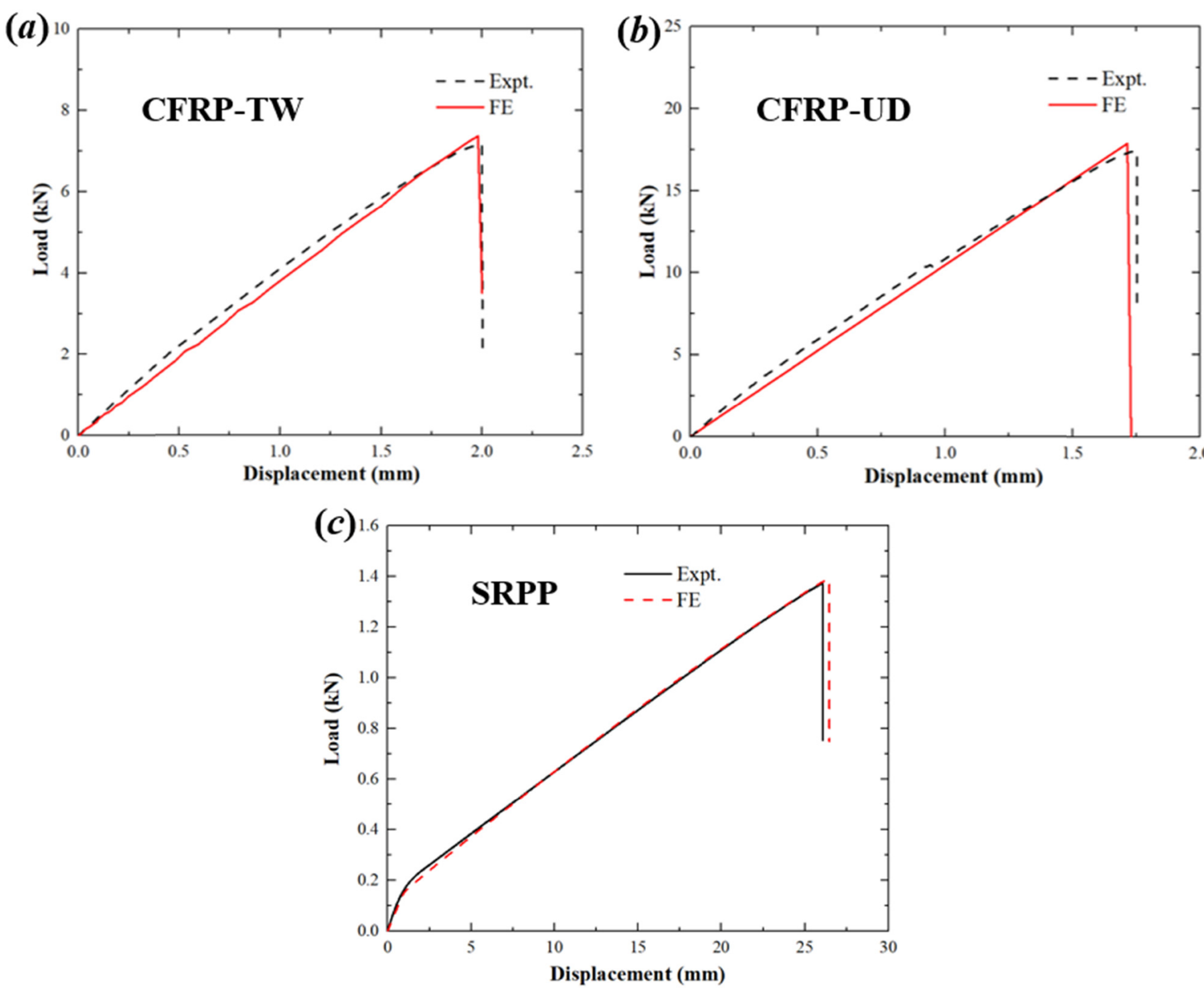

Figure 6: Experimental and numerical results of load *versus* displacement curves: (a) CFRP-TW, (b) CFRP-UD, and (c) SRPP.

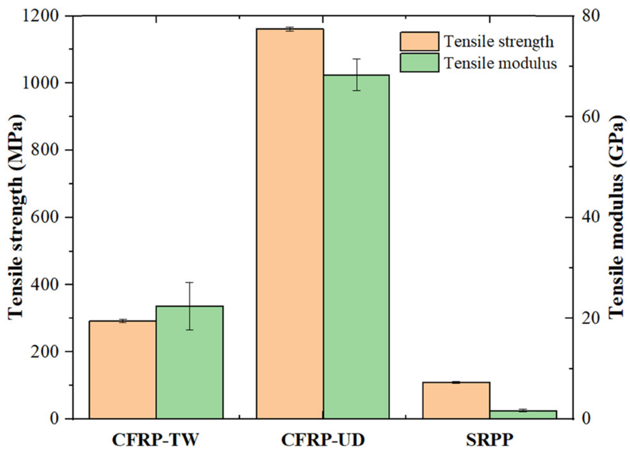

Figure 7: Tensile properties of CFRP and SRPP composite laminates.

with a UD pattern showed a higher tensile strength (X_T = 1160.38 MPa) than the TW pattern (X_T = 291.15 MPa) with the failure nominal strain of 0.017 and 0.013 in the CFRP-based system, respectively. It is because the UD pattern was aligned with the carbon fibre in a single direction, which provided exceptional strength and stiffness along the fibre direction. It is shown that tensile properties between CFRP-TW and CFRP-UD systems were due to the fibre orientation and alignment loading distribution. In the UD pattern, the fibres were found to be aligned along the loading direction, which is highly loaded in the direction of the fibres. In the TW pattern, not all fibres were aligned with the direction of the tensile loading, which caused stress concentrations and reduced the overall tensile strength. It was stated that there was some degree of dispersion for both CFRP patterns, which was observed in the literature [37].

Figure 5(b) illustrates the nominal stress *versus* nominal strain curves of the SRPP material under tensile loading, which is divided into elastic and plastic deformation stages. Initially, the SRPP specimen was deformed elastically, which had a linear relationship in the elastic deformation stage. The yielding point was caused by the tie molecules, which were connected to the highly oriented crystallites. The linear relationship between the nominal stress and strain increased the tensile loading for the plastic deformation stage. It was shown that SRPP material had tensile strength of X_T = 108.36 MPa with a nominal strain of 0.49. Figure 6(a) and (b) exhibits the experimental and numerical results of load *versus* displacement curves of CFRP composite materials with two patterns. It was concluded that the load *versus* displacement curves of the experimental results and the predicted results of the finite element modelling agreed fairly. For the TW pattern, the maximum tensile load was 7.17 kN with a displacement of 2.01 mm. For the finite modelling results, the maximum tensile load was 7.37 kN with a displacement of 1.98 mm, which was a 2.73% deviation between the experimental and numerical results. For the UD pattern, the maximum tensile load was 17.51 kN with a displacement of 1.75 mm. For the finite modelling results, the maximum tensile load was 17.90 kN with a displacement of 1.72 mm, which was a 2.24% deviation between the experimental and numerical results.

Figure 6(c) presents the experimental and numerical results of load *versus* displacement curves of SRPP material. It was demonstrated that there is a good agreement between the experimental and numerical results. The maximum experimental load was 1.36 kN with a displacement

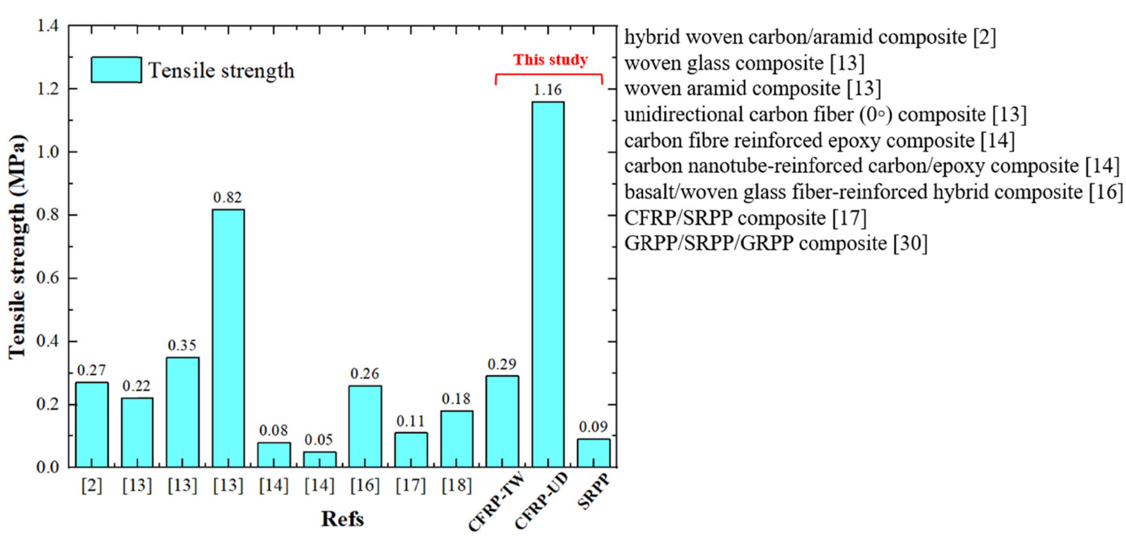

Figure 8: Comparison of tensile strength of various composite laminates in this work with the literature values.

Table 5: Summary of tensile properties of CFRP (TW and UD patterns) and SRPP composite laminates

Tensile properties	CFRP-TW	CFRP-UD	SRPP
Tensile strength (MPa)	291.15 ± 4.56	1160.38 ± 5.83	98.36 ± 2.03
Tensile strain (%)	1.32 ± 0.08	1.72 ± 0.05	49.05 ± 1.52
Tensile modulus (GPa)	22.39 ± 5.72	68.25 ± 5.15	0.65 ± 0.01

of 26.06 mm for the load *versus* displacement curve. The numerical maximum tensile load was 1.38 kN with a displacement of 26.45 mm, which was a 1.51% deviation between the experimental and numerical results. Figure 7 illustrates the comparison of tensile strength and modulus between CFRP-TW, CFRP-UD, and SRPP. CFRP-UD provides the maximum strength and stiffness in a specific direction, and it is suitable for load-bearing applications. CFRP-TW is ideal for multi-directional loading conditions where some trade-off strength is acceptable. Figure 8 compares the tensile properties of various composite laminates in the literature. It is pointed out that CFRP with a UD pattern provides the maximum tensile strength, and CFRP with a woven pattern exhibits moderate strength. The trade-offs between fibre orientation, woven pattern, and material types are compared to guide the selection based on the desired strength, cost, and potential application. Table 5 summarizes the tensile properties of CFRP and SRPP composite laminates in this study.

3.2 Failure behaviour of CFRP and SRPP composites

Figure 9(a) and (b) illustrates the failure behaviour of CFRP with two patterns before and after tensile tests. For the TW pattern, the fracture position occurred approximately in the middle of the tensile specimen. The brittle, flat failure at the fracture position was shown based on the TW pattern, which was neat and limited to a small area. It is because carbon fibres with TW patterns are interlaced, providing the same strength and stiffness in multiple directions. The carbon fibres were damaged following the fibre in a parallel direction to the tensile loading direction for the UD pattern. It was observed that carbon fibres were fractured, with the whole specimen splitting into pieces. It was mainly attributed to the fibre arrangement in the weft or warp direction, *i.e.*, perpendicular to the tensile loading direction. The matrix damage and delamination of CFRP

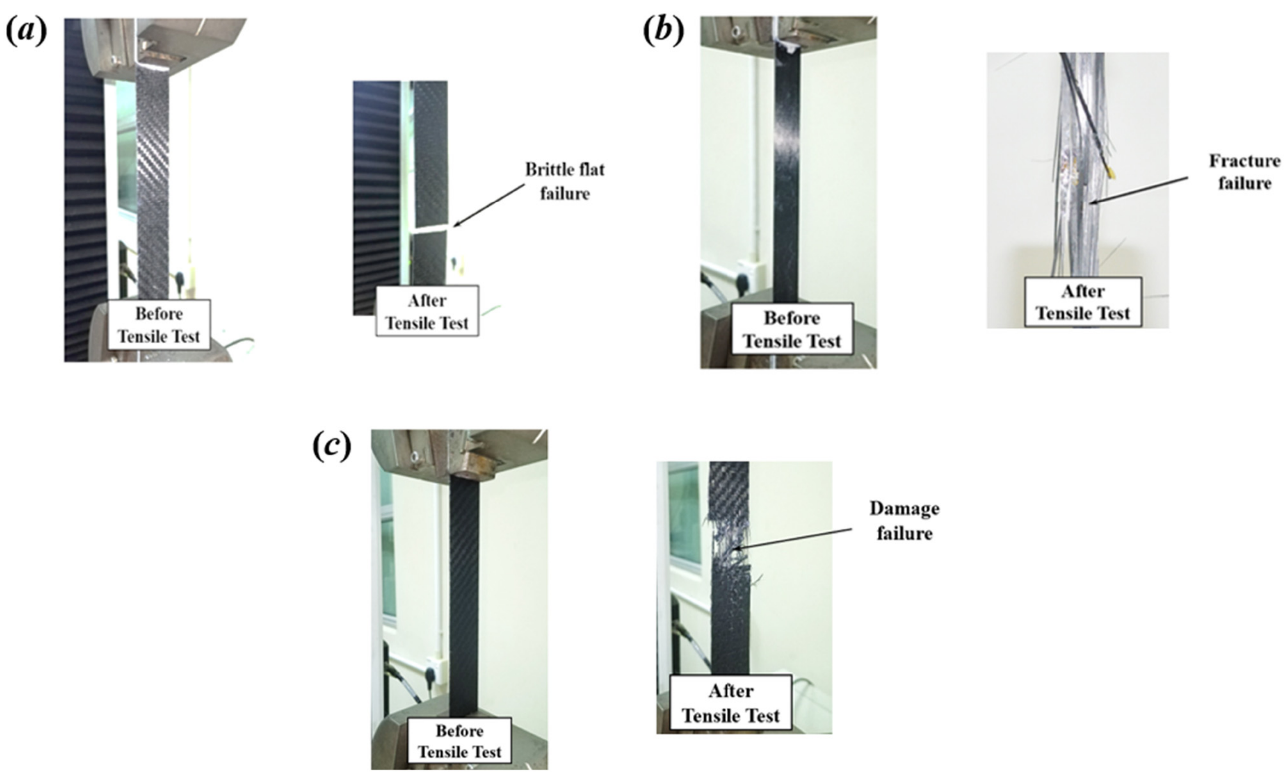

Figure 9: Example of the failure mode in CFRP and SRPP composites: (a) CFRP-TW, (b) CFRP-UD, and (c) SRPP.

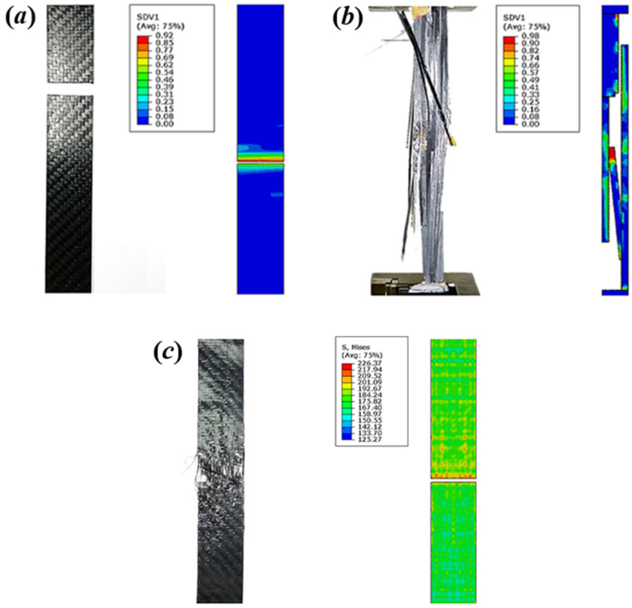

Figure 10: Experimental and numerical investigations on the failure behaviour of CFRP and SRPP composites: (a) CFRP-TW, (b) CFRP-UD, and (c) SRPP.

with UD patterns were observed. Figure 9(c) presents the failure behaviour of the SRPP specimen before and after the tensile test. It was demonstrated that damage failure occurred in the middle of the tensile specimen, which fell inside the length of the actual specimen. All longitudinal carbon fibres abruptly tore, and an amount of elastic recoil was observed after failure. It was determined that the realignment of the reinforced fibres was responsible for the initial shift in the slope of the nominal stress *versus* the nominal strain curve.

Experimental and numerical investigations on the failure behaviour of CFRP with two patterns are shown in Figure 10(a) and (b). It was exhibited that CFRP with two patterns had consistent failure behaviour between experimental and numerical results. It was found that brittle, flat failure was observed in the TW pattern, and carbon fibres were fractured and split into pieces in the UD pattern. Figure 10(c) presents the experimental and numerical investigations on the failure behaviour of SRPP material. It was demonstrated that there is a good agreement between the experimental and numerical results. The SRPP specimen was observed to exhibit consistent failure behaviour between experimental and numerical investigations.

Figure 11 presents some practical applications of CFRP and SRPP composites for various lightweight parts. CFRP and SRPP composite materials have increasingly become integral materials in the manufacturing industry, particularly for lightweight parts with required strength performance across various sectors. In automotive engineering, CFRP is largely utilized for components like wing, bonnet, wheel, and interior elements, providing an enhanced strength-to-weight ratio [38]. CFRP-based composite pressure vessels (CPVs) play a pivotal role in storing and transporting compressed gases and liquids [39]. Moreover, SRPP composite materials can be used in the manufacture of lightweight parts, such as luggage, protective armour, speaker cones, and ice skates [40]. It is highlighted that practical applications of CFRP and SRPP composites offer solutions in modern engineering. It further explored the importance

Figure 11: Practical applications of CFRP and SRPP composites for various lightweight parts [38].

of the tensile properties of CFRP and SRPP composites in sustainable contribution [41]. The integrated experimental and numerical investigations understand the tensile properties, which provides a framework for informed decision-making in designing and implementing CFRP and SRPP composites in various engineering domains [42], particularly in applications requiring lightweight and high-strength materials. These advanced composites are instrumental in various industries, including aerospace [43], automotive [44], and sport industries [45,46]. Furthermore, the CFRP composite remains crucial in high-performance applications with potential improvements in nanocomposites and manufacturing techniques, which reduces costs and boosts the mechanical performance. The wide application of SRPP composite material is poised to grow in industries prioritizing sustainability and cost-effective lightweight solutions driven by increasing environmental regulations leads in affordability, recyclability, and lightweight design for future engineering demands.

4 Conclusions

This article determines the tensile properties of CFRP and SRPP composites under experimental and numerical investigations. The experimental results show empirical insights into the tensile strength, tensile strain, and modulus of CFRP and SRPP composites. Finite element modelling is used to predict and validate the tensile response of both composite materials. For the TW pattern of CFRP, the maximum tensile load was 7.37 kN with 1.98 mm displacement, which was a 2.73% deviation between the experimental and numerical results. For the UD pattern, the maximum tensile load was 17.51 kN with 1.75 mm displacement, which was a 2.24% deviation between the experimental and numerical results. For SRPP, the numerical maximum tensile load was 1.38 kN with 26.45 mm displacement, which was a 1.51% deviation between the experimental and numerical results. The failure behaviour of CFRP and SRPP composites provides a good agreement between the experimental and numerical investigations. The findings address the promising potential of CFRP and SRPP composites in diverse engineering domains, emphasizing lightweight and high-strength applications.

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