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Effects on hybridization of interlayer composites and self-reinforced polypropylene

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1.0 INTRODUCTION

Composites are extensively used in several sectors, including aerospace and defence equipment, due to their high strength-to-weight ratio. Composites' growing popularity as a study subject among engineers and scientists has led to an expansion of its use in fields outside of transportation, including the shipbuilding, automobile, and construction industries [1, 2]. As an example, composites made of fiber-reinforced plastic (FRP) have remarkable energy absorption capacity and exceptional specific mechanical characteristics [3]. Also, any structural or component design has the potential to reduce bulk thanks to the beneficial mechanical qualities of FRP composites [4-6]. Crashworthiness structures may be effectively implemented using glass and carbon based FRP composites because of their dependable mechanical qualities, accessibility, and manufacturability [7]. Also, light-loaded constructions often make use of aramid FRP because of its high tensile strength and outstanding fatigue resistance [8]. The use of FRP composites that include hybridisation has been on the rise as of late. Because of the substantial gain in structural flexibility compared to conventional FRP composites, this method is attracting a lot of attention. A number of benefits, including increased structural stiffness, specific strength, failure strain, resilience, and material cost, may be realised by the hybridisation of composites, which allows for the merging and generation of distinct fibre properties. To save costs, researchers have looked at hybrid composite constructions made of carbon and glass fibres that are weaved together [9, 10]. Two typical approaches to composite hybridisation are interlayer and intralayer, with much prior research focussing on how to enhance flexural characteristics. Many possible hybrid combinations may be further investigated, as it has shown clearly [11, 12]. Another thermoplastic composite with good strain-to-failure and high tensile strength was found in another investigation to be self-reinforced polypropylene (SRPP). In addition, the material has high impact strength and outstanding fracture resistance; as a result, SRPP is seen as an additional possibility for hybridisation and composite research [13, 14]. The main objective of this research is to analyse the consequences of combining various kinds of fibres with SRPP in interlayer composites. Fibres made of carbon, glass, and aramid were used in this research. For the aim of characterising the impacts on thermoset and thermoplastic composite hybridisation, SRPP sheets are also included into the mixture. Given that study, five composite designs were produced using conventional hand lay-up technique. Subsequently, the fabricated specimens undergone the tensile and three-point flexural tests according to ASTM standards to determine the mechanical characteristics of each design [15, 16].

2.0 COMPOSITE MATERIALS PREPARATION

In this work, several types of fibres are used such as carbon, glass and aramid fibres. The epoxy and slow-type hardener were selected as the mixture of matrix. Furthermore, the hybrid structure has included several thermoplastic sheets of self-reinforced polypropylene (SRPP). Interlayer hybrid structures were chosen as the method of combining different materials [17]. Each weave orientation of the raw material fabrics and sheets were decided according to accessibility and their basic characteristics. In this case, plain glass, aramid fabrics, and twill carbon fabric were in stock. According to Koricho and Belingardi [18], plain and twill weave fibre types are the finest in terms of stability, durability and balance.

Table 1 shows the proposed design structures and stacking sequence for the test specimens, which apply to both tensile and three-point flexural tests. Each design shall have three specimens fabricated for respective tests to ensure the quality of the result. All design structures retained epoxy resin as the sole matrix material, whereas the weave alignment angle was fixed to 0°/90°. Moreover, all composite specimens were produced by means of the conventional hand lay-up method [19]. Noted that all model arrangements are constantly made of five plies of fabrics and sheets. Subsequently, Figure 1 denotes the orientation of fibre fabrics and their stacking sequences for both types of composites. In addition, a flow chart of composite manufacturing process by conventional hand lay-up technique is illustrated in Figure 1(c). Experimental configurations and each specimen size are consistent with ASTM standards, which refers to D3039 and D7264 for tensile test and three-point flexural test, respectively [15, 20].

Table 1. List of composite structures and their stacking arrangements

Model No.	Composite	Stacking Order	Type
1	Carbon fibre-reinforced plastic (CFRP)	CCCCC	Single
2	Glass fibre-reinforced plastic (GFRP)	GGGGG	Single
3	Carbon/Aramid fibre-reinforced plastic (CAFRP)	CACAC	Hybrid
4	CFRP/SRPP	CSCSC	Hybrid
5	GFRP/SRPP	GSGSG	Hybrid

Remarks:
C: Carbon, G: Glass, A: Aramid, S: Self-reinforced Polypropylene

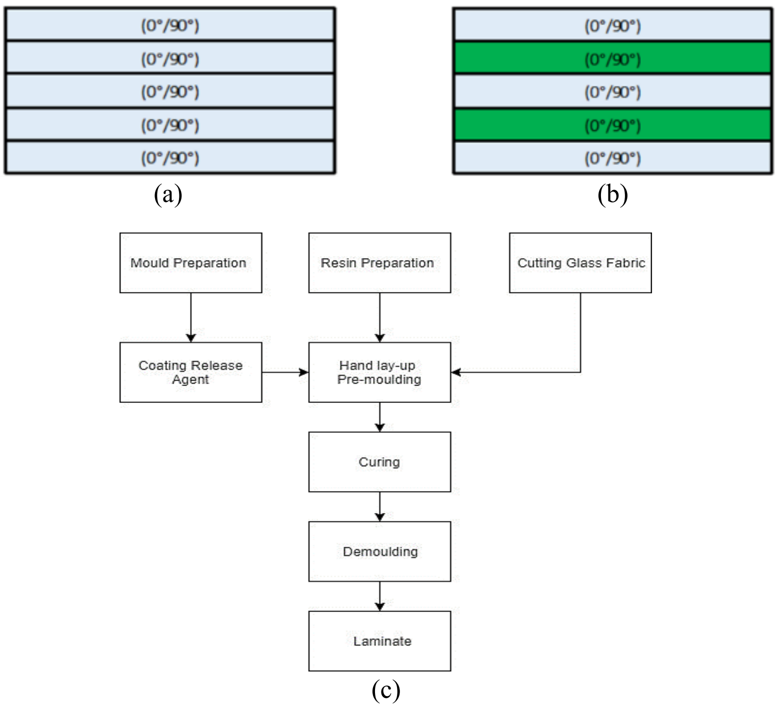

Figure 1. Schematic fibre direction with lay-up arrangements for the composite of: (a) single material, (b) hybrid type and (c) flow chart of the composite manufacturing process by hand lay-up technique [21]

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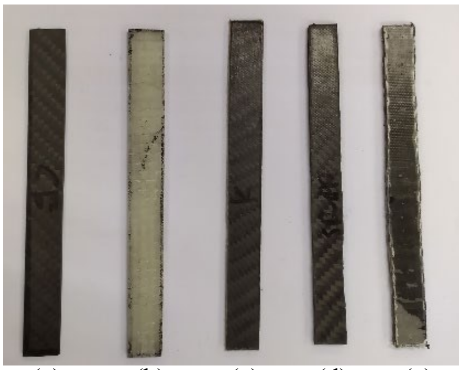
2.1 Preparation of Testing Specimens

The process of composite specimen fabrication started with cutting the fibre into the size of approximately 350 mm in width and length. Referring to the hybrid composite that involved SRPP layers, sandblasting process on both sides of the SRPP sheet's surface were done beforehand to increase the bonding potential with woven fibre laminates. Next, epoxy resin by EpoxAmite was mixed with the catalyst slow-type Hardener, whereby the mixture ratio was set to 3:1. To produce a consistent matrix mixture throughout all specimens, the low-speed stirring process was accomplished within 4 minutes using an automatic overhead stirrer machine. This method significantly avoided the presence of air bubbles in the epoxy and hardener mixture.

Before starting the lay-up process, two glass panels and a roller were cleaned using acetone to avoid any impurities on the surface of composite laminate. Then, the Stoner Miracle Gloss (Maximum 8 2.0) anti-adhesive agent was applied on the surface of glass panels to ensure the smooth process of composite laminate removal after cured. Next, the prepared first layer of fibre was placed on the glass panel and resin mixture was poured on the fibre. The mixture was then swept evenly throughout the fibre by using the roller. This was done carefully to establish good absorption by all the fibres and to avoid air bubbles trapped inside the laminates.

This process was then repeated for the subsequent layers in accordance to the stacking order. After all layers had been stacked completely, a 5 kg glass panel were positioned on topmost to evenly press the laminates during curing. The laminates were left for 24 hours of curing process at room temperature. After removing the laminates from the glass panels, they were cut out using the wood saw machine to produce specimens as required by ASTM standards. The cutting quality is satisfactory for straight cuts and simple shape. For finishing purposes and to achieve more accurate dimensions, a grinding process was employed using a belt and disc sander machine. The tensile specimens were dimensioned with 250 mm in length and 25 mm in width, while bending specimens were prepared with size of 130 mm in length and 13 mm in width. Accordingly, each model structures consisted of three samples for both types of testing. Figure 2 displays the five design structures of composite laminate in flexural test specimen size.



(a) (b) (c) (d) (e)

Figure 2. Sample of composite laminate specimens: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP and (e) GFRP/SRPP

Table 2 reviews the composite's basic specimen specifications accordingly. Three measurements for each parameter were conducted and value acquired were fairly consistent, showing good level of accuracy. Here, each design's average weight, thickness and density are compared. The carbon-based composites are clearly the lightest and thinnest, whereby glass based composites are the heaviest. Meanwhile, the inclusion of SRPP sheets between the layers has significantly increased the overall thickness of the composite. It is noted that density measurement was conducted using AlfaMirage: MD-300S electronic densimeter. The attained density data were relatively consistent between all specimens, indicating the process's conformity during fabrication.

Table 2. Specifications of flexural specimens

Model No.	Stacking order	Average weight (g)	Average thickness (mm)	Average density (g/cm^3)
1	CCCCC	3.99	1.70	1.358
2	GGGGG	8.02	2.95	1.646
3	CACAC	5.06	2.70	1.288
4	CSCSC	5.78	3.30	1.002
5	GSGSG	6.28	3.35	1.125

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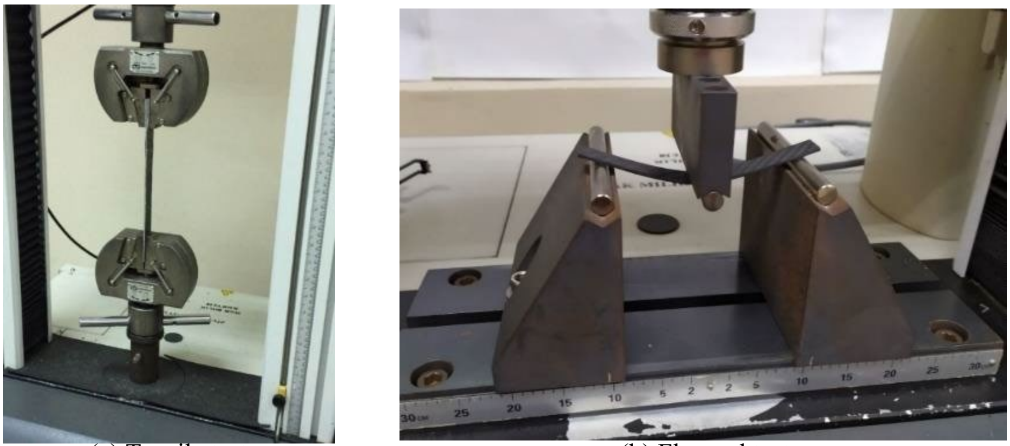
3.0 EQUIPMENT AND EXPERIMENTAL TECHNIQUES

Instron's universal testing machine (Series 3369) was utilized to determine the static mechanical behaviour of composite specimens in accordance to the ASTM guidelines. The test speeds were set at 2 mm/min and 1 mm/min for the measurement of tensile properties and flexural properties, respectively. As illustrated in Figure 3, each specimen for all composite structures were carried out and their mechanical response were recorded and analyzed.



(a) Tensile test (b) Flexural test

Figure 3. Testing set-up: (a) Tensile test and (b) Flexural test

The composite samples will experience both elastic and plastic deformation stages when subjected to tensile loading. In this particular test, the sample initially exhibited elastic deformation, resulting in a linear correlation between the applied load and extension. These two values were subsequently employed to assess the curves for tensile stress versus tensile strain. The equations below were used to calculate the tensile stress and strain in this context.

$$\sigma = \frac{P}{A} \quad (1)$$

$$\varepsilon\varepsilon = \frac{L_{ff} - L_o}{L_o} = \frac{\Delta L}{L_o} \quad (2)$$

$$E = \frac{\sigma}{\varepsilon\varepsilon} = \frac{PL_o}{A\Delta L} \quad (3)$$

where σ represents the tensile stress, $\varepsilon\varepsilon$ signifies the tensile strain, P denotes the axial load, and A denotes the initial cross-sectional area of the specimen. It is important to observe that L_{ff} represents the ultimate length of the specimen, while L_o designates the original length of the specimen.

During the three-point flexural experiment, the maximum bending strength and flexural modulus are calculated for each design specimen using the equation below [22].

$$\sigma = \frac{3PL}{2bh^2} \quad (4)$$

$$E = \frac{L^3P}{4bh^3y} \quad (5)$$

In this context, the parameters are defined as follows: The beam width is represented by b in millimeters, the beam thickness is denoted by h in millimeters, the support span length is indicated as L in millimeters, the applied force is represented by P in Newtons, the stress at the outer surface of the mid-span is denoted as σ in megapascals (MPa), and y represents the distance covered by the applied load.

4.0 RESULTS AND DISCUSSION

A total of 30 specimens were tested using the Instron testing machine for both tensile and flexural modes. All 5 variants of composite specimens have three samples each, whereby 15 in total for the respective test. Using three replicates to ensure that the reported properties are accurately represented by the material's behaviour. This provides more reliable and precise results. During the procedures, the measured properties were the tensile and flexural stress, modulus of elasticity and strain at failure. This composite data set shall be useful as input for any finite element analysis in future works [16].

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4.1 Tensile Test Results

The failed tensile specimens are demonstrated in Figure 4. Figure 5 represents the tensile stress-strain curve for each composite specimen. The mechanical response was compared between all structures and the tensile stress-strain curve is illustrated in Figure 6. It can be seen that the tensile strength and modulus for each design structure clearly showed different characteristics.

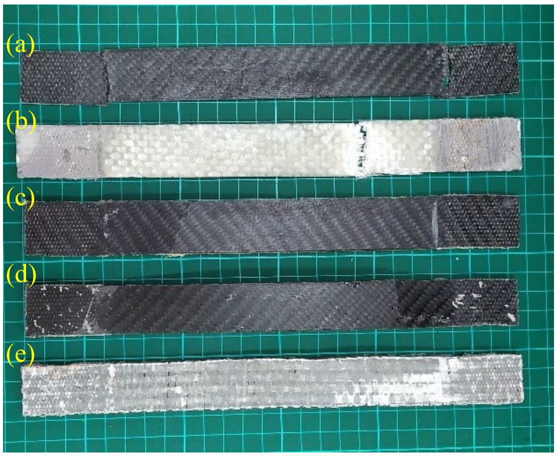
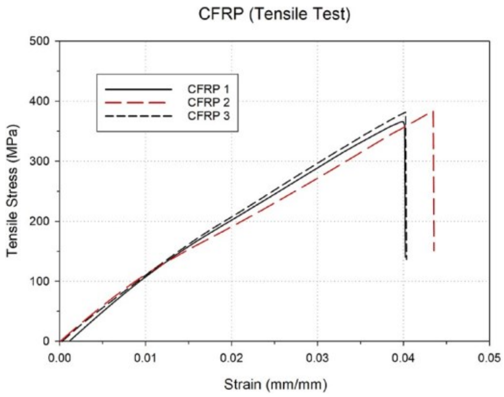
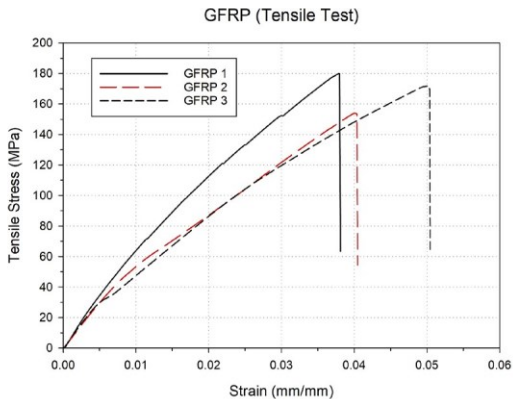


Figure 4. Failed tensile specimens after undergone test: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP and (e) GFRP/SRPP



(a)



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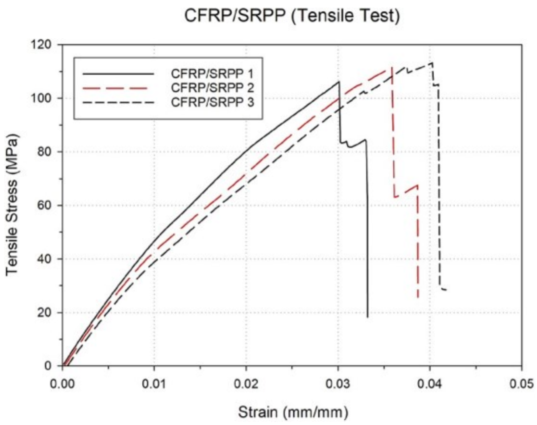

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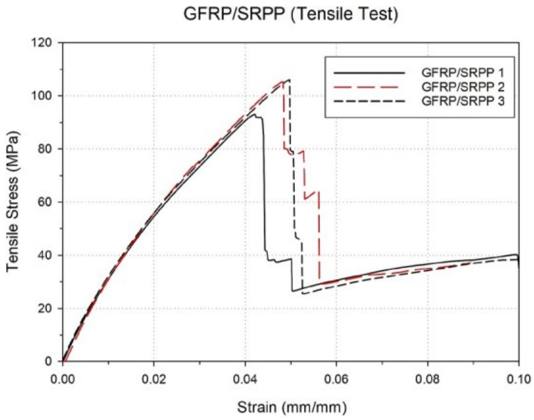

(d)

Figure 5. Tensile stress-strain curve results for three samples of each composite design: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP

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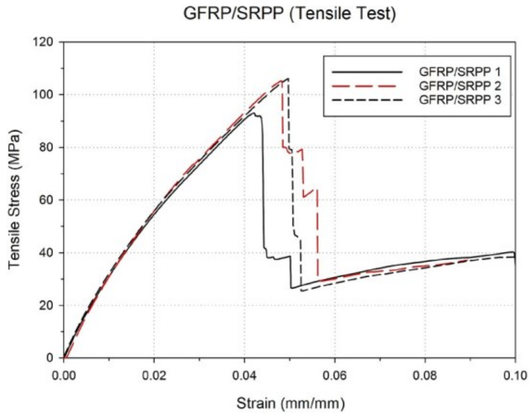

Figure 5. (cont.) (e) GFRP/SRPP

CFRP specimen displayed the best tensile strength and elastic modulus among the other structures. For hybrid structures comparison, CAFRP coupon exhibited good tensile response, which indicated impressive interlayer bonding in-between different weave of fibres. In contrast, GFRP/SRPP hybrid specimen exposed a relatively high ductility at the expense of tensile strength and elastic modulus. As a result, both GFRP/SRPP and CFRP/SRPP hybrid composites scored the lowest tensile strength, which could be due to poor bonding character between the woven fibre and PP sheets.

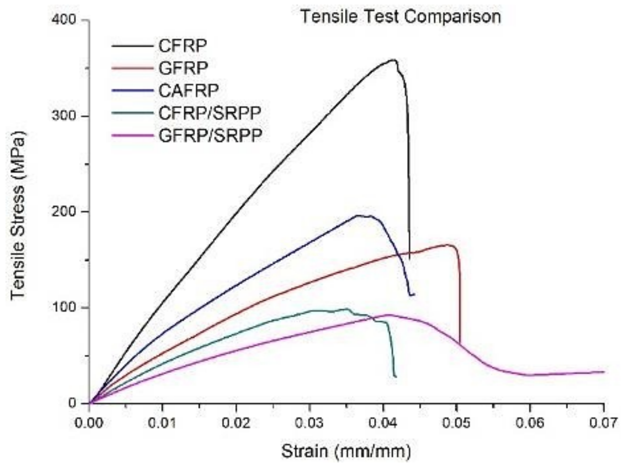

Figure 6. Tensile stress-strain curves at various composite configurations

Elastic modulus and tensile strength values obtained by each composite structures were extracted, compared and presented in Figure 7. The CFRP structure was noticed to have 46% and 33% higher than CAFRP specimen in terms of tensile strength and elastic modulus, respectively. However, the hybridization of CFRP/SRPP has decreased the tensile strength by 71% when compared to the value obtained by single type CFRP. It can be concluded that insertion of SRPP sheets to create hybrid composite structure showcased a significant decrease on mechanical response in tensile mode.

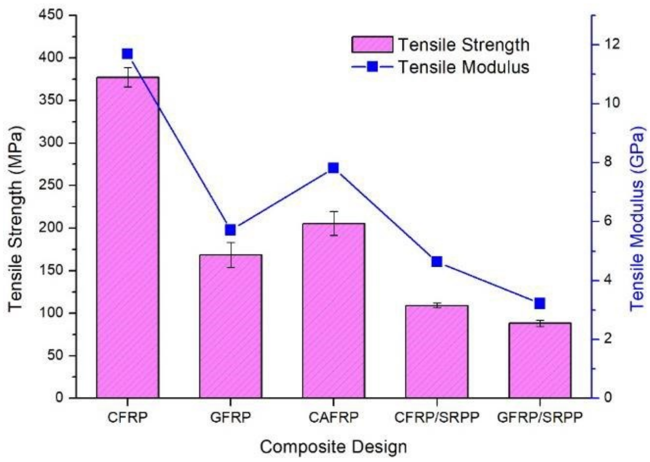

Figure 7. Tensile properties comparison with different composite configurations

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4.2 Three-Point Flexural Result

Flexural composite specimens undergone a series of three-point bend test are shown in Figure 8. Figure 9 characterizes the flexural stress-strain curve for respective composite samples. Meanwhile, Figure 10 presents the comparison of stress-strain curve for the flexural response. This result suggests that hybrid CAFRP specimens demonstrated a very high flexural response, compared with those of the full carbon configurations. The stress–strain curve for CAFRP structures clearly indicated that the presence of aramid layers stacked in-between the carbon plies pointedly enhanced the flexural strength. Unsurprisingly, hybridization of GFRP/SRPP and CFRP/SRPP did not affect the mechanical performance in a positive way. Alike the tensile results, SRPP hybrid specimens displayed lowest flexural strength. The flexural strength of the GFRP/SRPP and CFRP/SRPP configuration from the experiments shows decreases of 58% and 25% compared with those of the full carbon and glass configurations, respectively. SRPP-based composites have shown the capability to generate higher strain values in this test. The study emphasizes the toughness characteristics of SRPP-based hybrids.

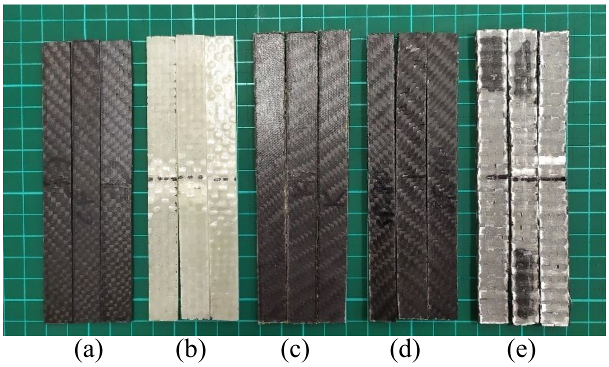


Figure 8. Damaged flexural specimens: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP and (e) GFRP/SRPP

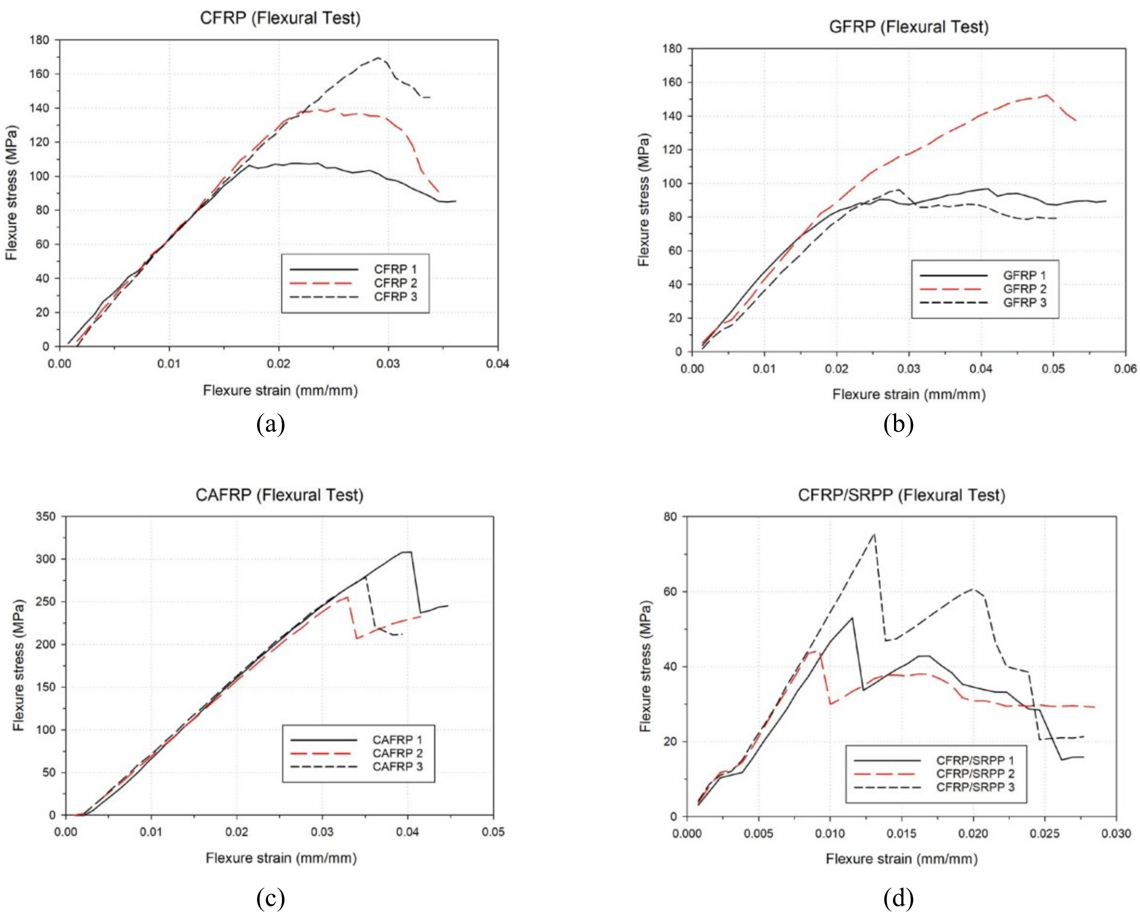
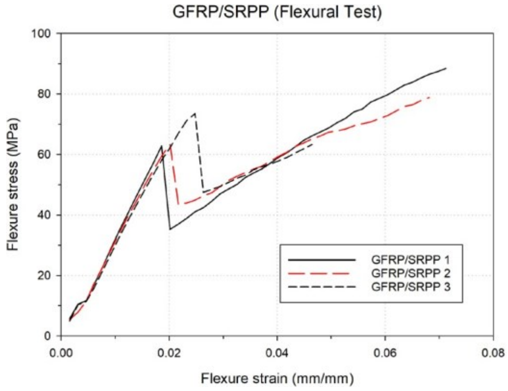


Figure 9. Flexural stress-strain curve results for three samples of each composite design: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP



(e)

Figure 9. (cont.) (e) GFRP/SRPP

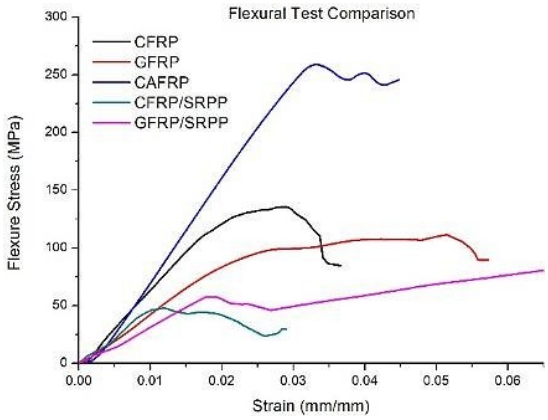


Figure 10. Flexural stress-strain curves compared between composite structures

Furthermore, flexural response by the composite specimens were summarized in Figure 11. The CAFRP structure demonstrated superior performance compared to the CFRP structure, exhibiting higher results by 50% in flexural strength and by 19% in flexural modulus, respectively.

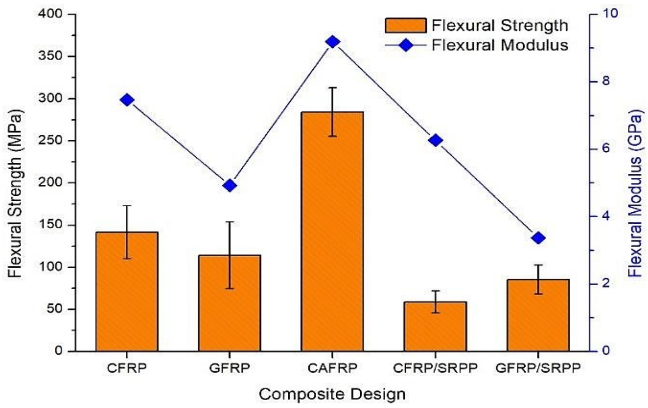


Figure 11. Flexural properties comparison with different composite configurations

Referring to the experimental results, composite structures of single-type CFRP and hybrid type CAFRP reveals outstanding response in terms of tensile and flexural behaviour, respectively. Regarding tensile strength and modulus, the current work demonstrates that the achievements of CFRP and GFRP are relatively higher when compared to the results presented previously by Hunain et al. [12]. It can be seen in both tests that most of the specimens responded linearly up to the peak load. Dong et al. [22] mentioned that positive hybrid effects exist by substituting carbon fibres with other material such as glass fibres, as proven in their flexural test. In agreement to that, this present work demonstrates that hybridization of carbon-aramid fibre has shown a very positive increase regarding flexural strength and modulus. This indicates the impact of aramid plies, which supports the absorption of the flexural energy. In contrast, hybridization between thermoset composites and thermoplastic SRPP obviously displays their inability to survive high load. The weak bonding factor created delamination between their plies, which contributed to the failure. Summary on mechanical properties of the composite structures extracted from tensile and flexural experiments is listed in Table 3. This study confirms that composite containing SRPP laminates produce high toughness but low stiffness characteristics, whereas interlayer composites indicate the features of high strength and stiffness but low elongation. Nevertheless, it is important to acknowledge that the relatively small sample size in this study may have influenced the results. Increasing the sample size could potentially enhance the consistency of the results.

Table 3. Summary of mechanical characteristic results

Composite Type	Tensile modulus, E_t (GPa)	Tensile strength, σ_{ut} (MPa)	Flexural modulus, E_f (GPa)	Flexural strength, σ_f (MPa)
CFRP	11.69	377	7.47	141
GFRP	5.71	169	4.93	114
CAFRP	7.82	205	9.19	284
CFRP/SRPP	4.63	109	6.27	59
GFRP/SRPP	3.22	88	3.37	85

5.0 CONCLUSIONS

The study aimed to explore the tensile and flexural properties of composite configurations with varying interlayer hybridizations. Five composite configurations comprising various woven fibre types and self-reinforced polypropylene (SRPP) sheets were manufactured using the hand lay-up process. Tensile experimental results revealed that CFRP exhibited the highest tensile strength, surpassing CAFRP by 46% in strength and 33% in elastic modulus. However, introducing CFRP/SRPP hybridization significantly reduced tensile strength by 71% compared to pure CFRP. Nevertheless, during the three-point flexural test, hybrid CAFRP structures exhibited superior flexural strength, outperforming CFRP with a 50% higher flexural strength and a 19% greater flexural modulus. These findings indicate the potential of CAFRP for material stiffness. The inclusion of SRPP sheets in hybrid configurations diminished both tensile and flexural strengths, with GFRP/SRPP and CFRP/SRPP configurations showing 58% and 25% reductions, respectively, in flexural strength compared to full carbon and glass configurations. Weak interlayer bonding of SRPP was identified as a primary influence, despite its ability to create higher strain values. Overall, the study elucidates the trade-off between stiffness and toughness in different composite designs, highlighting the versatility of SRPP-based hybrids.

6.0 ACKNOWLEDGEMENT

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