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RESEARCH ARTICLE

Effects on hybridization of interlayer composites and self-reinforced polypropylene

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ABSTRACT - In recent years, there has been increasing attention to develop a high-strength, lightweight composite as a potential substitution for conventional materials in various sectors, whereby most studies have focused on the mechanical performances of fibre-reinforced plastic (FRP) such as carbon, glass and aramid. In contrast, the hybrid composites are less common, though are viewed to have substantial potential in terms of flexibility and capability to merge the benefits of different composites. In this study, five composite designs consisting of several types of woven fibres and self-reinforced polypropylene (SRPP) sheets have been fabricated using the hand lay-up procedure. Several designs are arranged based on the interlayer hybridization mode. The static mechanical properties of the composite designs were examined through the standard tensile and three-point flexural tests. The outcomes attained from the experimental works revealed that carbon fibre-reinforced plastic (CFRP) produced the best tensile characteristics. The CFRP structure displayed 46% higher tensile strength and a 33% greater elastic modulus compared to the CAFRP specimen. Meanwhile, hybrid carbon/aramid fibre-reinforced plastic (CAFRP) pointedly enhanced flexural properties in comparison with single type and other hybrid composites, whereby CAFRP structure outperformed the CFRP structure, exhibiting superior results with variations of 50% and 19% in flexural strength and modulus, respectively. Though the inclusion of SRPP layers in-between the hybrid setup exhibited a decrease in both tensile and flexural strength, but improved the total strain level. The evidence from this study suggests that FRP composites indicate structures of high strength and stiffness but low elongation, whereas SRPP-based composites improve toughness but reduce stiffness characteristics.

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1.0 INTRODUCTION

Composite materials are often acknowledged as high-strength and lightweight materials, hence being widely applied in several industries such as defence machinery and aerospace segment. Composites have been an attractive research topic for engineers and scientists in recent years, and therefore, have increased their application to other sectors, such as automotive, construction, rail transportation and ship industry [1, 2]. For instance, fibre-reinforced plastic (FRP) composites possess outstanding specific mechanical properties and excellent energy absorption capability [3]. Moreover, the favourable mechanical properties of FRP composites prove the potential of mass reduction for any structural and component design [4-6]. Glass and carbon based FRP composites are among the reliable candidates for application of crashworthiness structure due to their mechanical properties, availability and manufacturability [7]. Besides that, the aramid FRP are another type of composite with high tensile strength and excellent fatigue resistance, thus being used in light-loaded structures [8].

Recently, there has been an increasing trend in the hybridization of FRP composites. This approach draws much interest due to significant improvement in terms of structure flexibility compared to typical FRP composites. Hybridization of composites can merge and generate different fibre characteristics, consequently expanding the advantages such as structure stiffness, specific strength, failure strain, robustness and material cost. For example, hybrid composite structures that consist of woven carbon and glass fibres have been studied, with the main objective of cost reduction [9, 10]. Interlayer and intralayer are the two common methods of composite hybridization, whereby previous work mainly explains the improvement of flexural properties. It has conclusively shown that many potential hybrid combinations can be further explored [11, 12]. In a different study, a self-reinforced polypropylene (SRPP) is another thermoplastic composite with high tensile strength and strain-to-failure properties. Besides, the material has good impact strength and excellent fracture resistance, therefore the SRPP is observed as another potential for composite research and hybridization [13, 14].

The primary purpose of this study is to observe the effects on the hybridization of interlayer composites of several fibre types and SRPP. Materials used in this study are carbon, glass and aramid fibres. Also included in the mix are SRPP sheets for the purpose of defining the effects on the hybridization of thermoset and thermoplastic composites. In this

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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

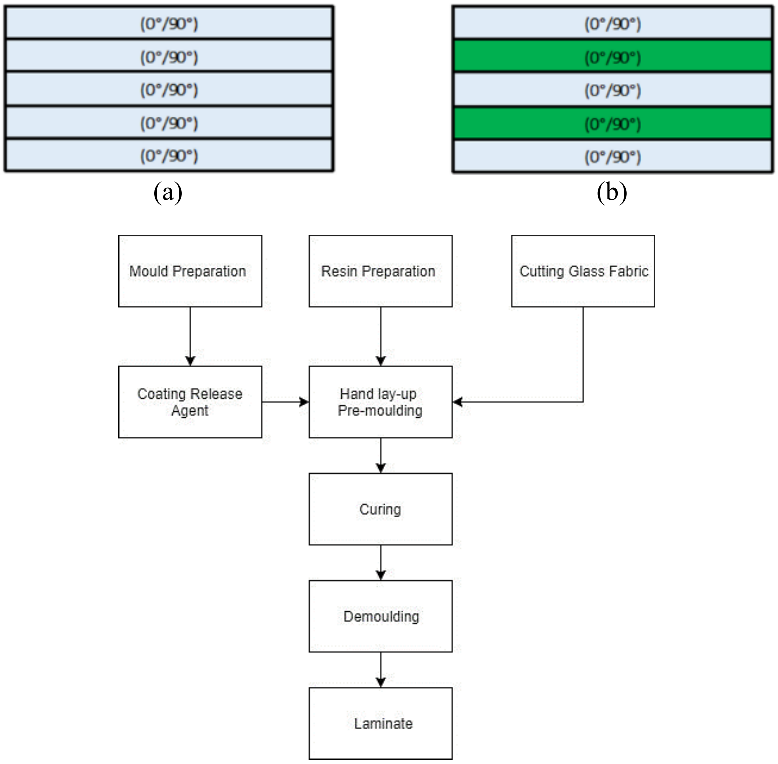
In this work, several types of fibres are used such as carbon, glass and aramid fibres. The epoxy and slow-type hardener were selected as the mixture of matrix. Furthermore, the hybrid structure has included several thermoplastic sheets of self-reinforced polypropylene (SRPP). Interlayer hybrid structures 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



(a) (b) (c)

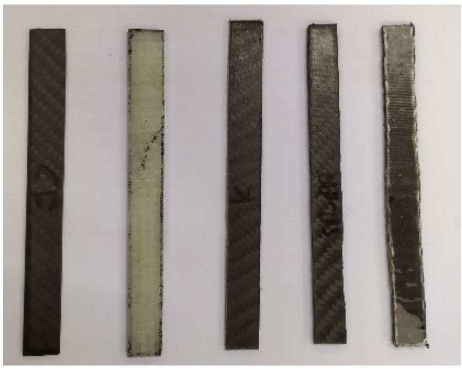
Figure 1. Schematic fibre direction with lay-up arrangements for the composite of: (a) single material, (b) hybrid type and (c) flow chart of the composite manufacturing process by hand lay-up technique [21]

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

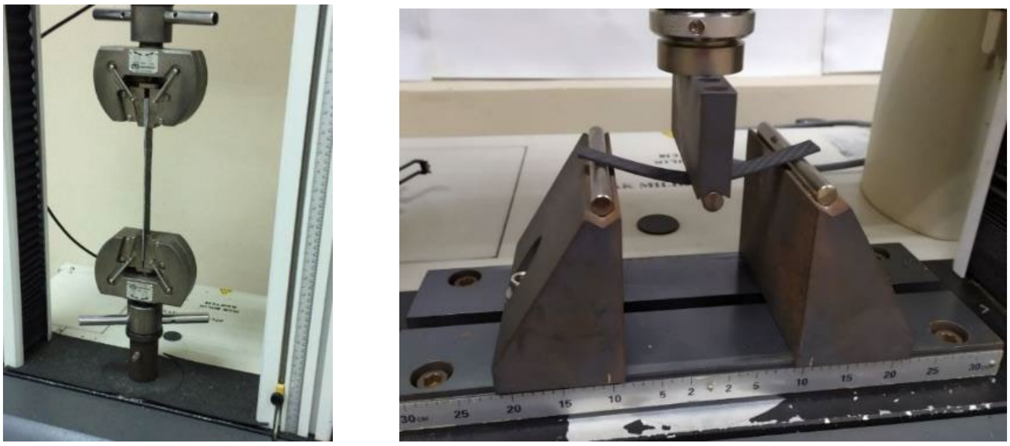
Table 2 reviews the composite's basic specimen specifications accordingly. Three measurements for each parameter were conducted and value acquired were fairly consistent, showing good level of accuracy. Here, each design's average weight, thickness and density are compared. The carbon-based composites 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

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.

$$\sigma = \frac{P}{A} \tag{1}$$

$$\varepsilon = \frac{L_f - L_o}{L_o} = \frac{\Delta L}{L_o} \tag{2}$$

$$E = \frac{\sigma}{\varepsilon} = \frac{PL_o}{A\Delta L} \tag{3}$$

where σ represents the tensile stress, ε 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_f 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].

$$\sigma = \frac{3PL}{2bh^2} \tag{4}$$

$$E = \frac{L^3 P}{4bh^3 y} \tag{5}$$

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].

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.

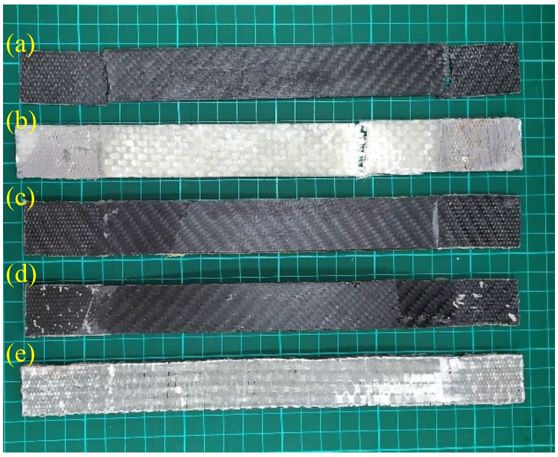
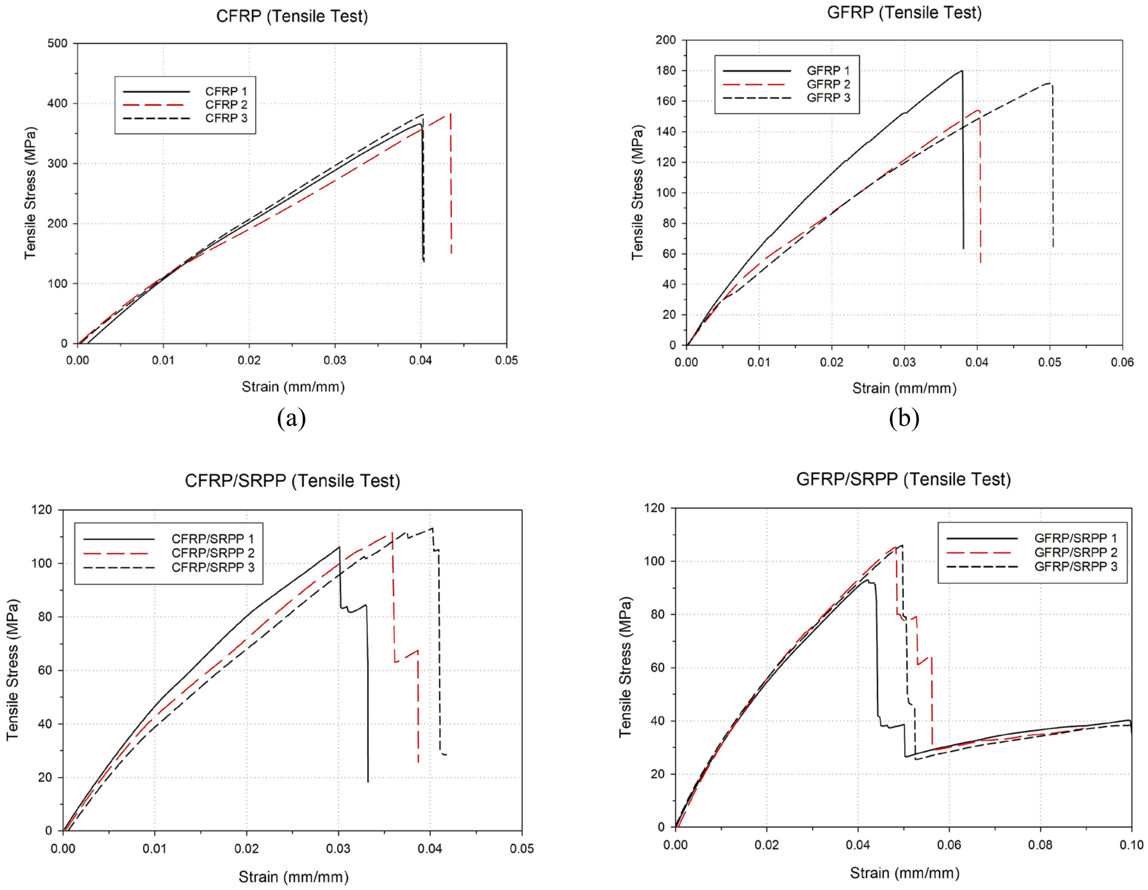


Figure 4. Failed tensile specimens after undergone test: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP and (e) GFRP/SRPP



(a) (b)

(c) (d)

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

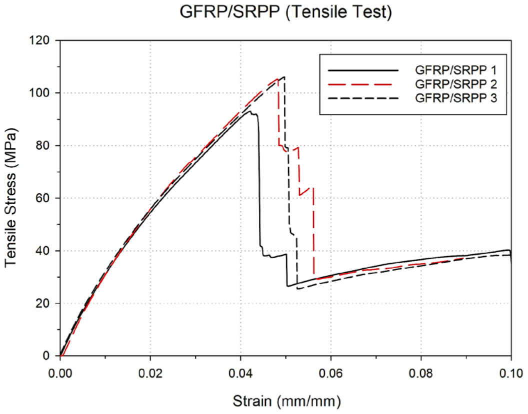


Figure 5. (cont.) (e) GFRP/SRPP

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.

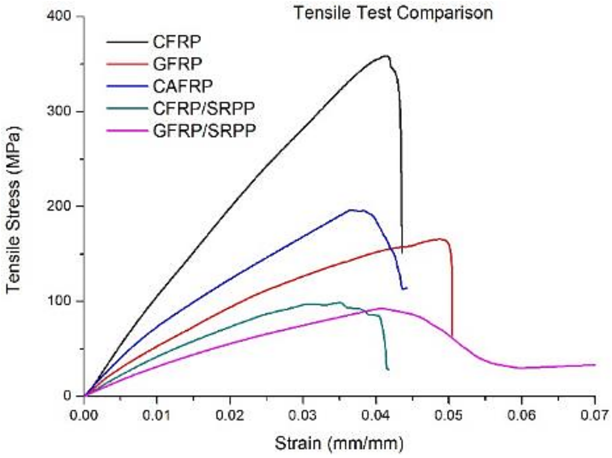


Figure 6. Tensile stress-strain curves at various composite configurations

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.

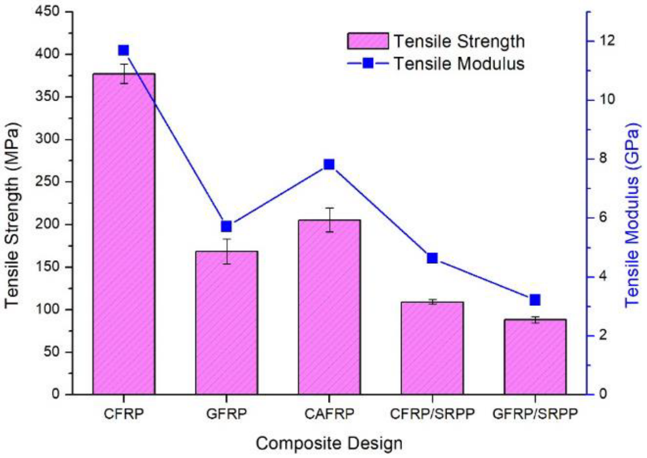
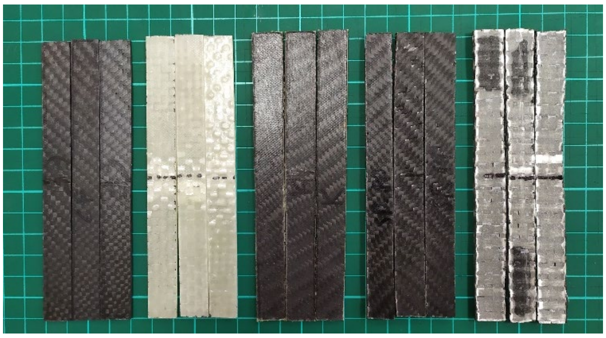


Figure 7. Tensile properties comparison with different composite configurations

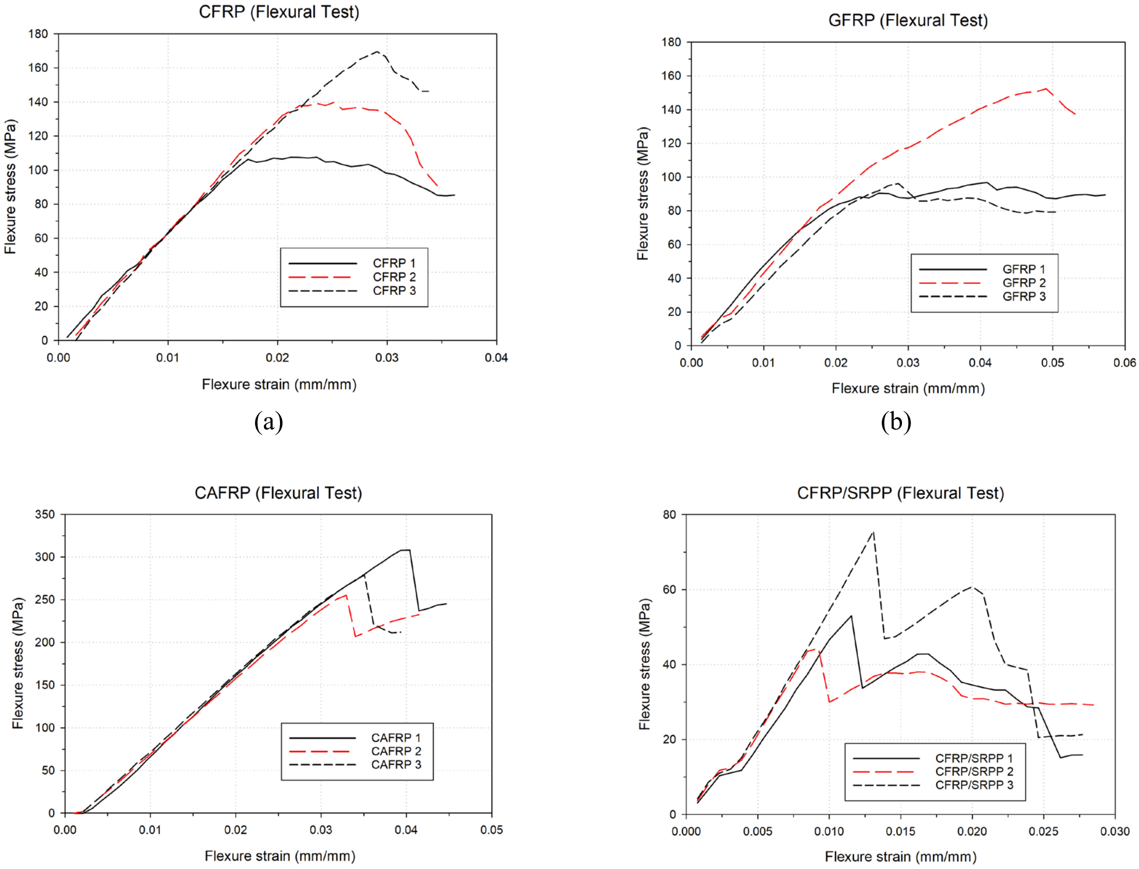
4.2 Three-Point Flexural Result

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.



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

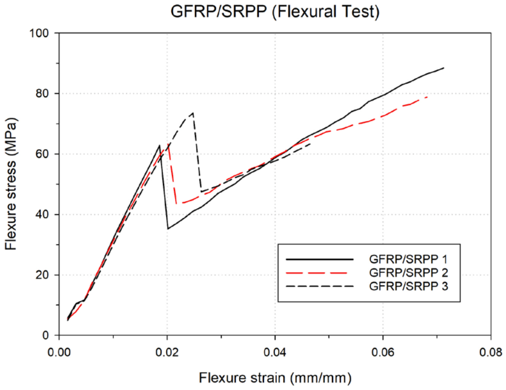
Figure 8. Damaged flexural specimens: (a) CFRP, (b) GFRP, (c) CAFRP, (d) CFRP/SRPP and (e) GFRP/SRPP



(a) (b)

(c) (d)

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

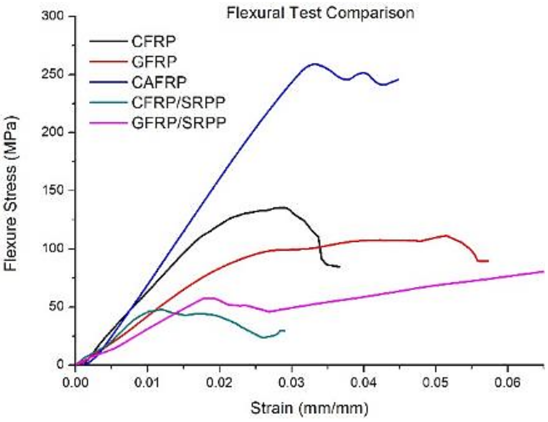


Figure 10. Flexural stress-strain curves compared between composite structures

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.

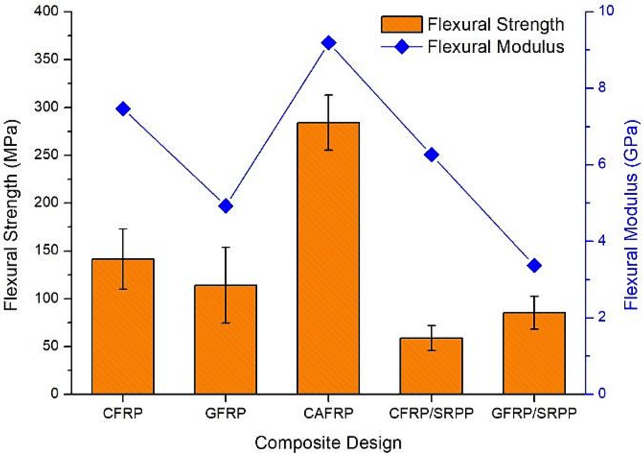


Figure 11. Flexural properties comparison with different composite configurations

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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