

Mechanical Uniaxial Tensile Performance of Hybrid Glass/Carbon Woven Composites

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Abstract

Carbon fibres are widely recognized for their remarkable strength-to-weight ratio, but their high cost and limited lifespan have prompted researchers to explore alternative materials. One promising solution is the use of hybrid composites, which combine carbon fibres with other fibre types, to maintain mechanical strength at optimal levels while reducing costs. A scientific study was conducted to investigate the impact of stacking configuration on hybrid glass/carbon woven composites. The study established eight stacking configurations based on the incorporation of identical and non-identical weave structures at the outermost layers. The hybrid glass/carbon woven composites were fabricated using the hand lay-up approach, with epoxy resin used as the polymer matrix. The results of the study showed that the hybrid B configuration yielded the highest tensile strength at 322.75 MPa, while the hybrid F sequence generated the lowest tensile strength at 169.00 MPa. The findings from this study indicated that the incorporation of weave structures with longer yarn floats in a non-identical arrangement at the outermost layer resulted in improved uniaxial tensile strength performance.

1. Introduction

Woven composites are created by layering textile fibres, which may be of the same type or various types. The former are referred to as single-fibre composites, while the latter are known as hybrid composites. The fabric stacking method is widely used by researchers to create hybrid woven composites, which offers two significant advantages: low manufacturing costs and flexibility in the composite fabrication process. This method allows researchers to obtain woven fabrics with two or more different textile fibres without being involved in the production process, resulting in reduced manufacturing expenses. Furthermore, the flexible fabric stacking approach enables researchers to experiment with multiple variations in fabric layer sequences, which can be used to evaluate and enhance the flexural and tensile strengths of hybrid composites.

A blend of matrices in a single reinforcing fibre or a combination of two or more fibres in a polymer matrix makes up hybrid composites. Additionally, hybrid composites can combine the two methods. Historically, natural-synthetic, natural-natural as well as synthetic-synthetic fibre types have been potential combinations for hybrid composites [1]. The main goal of hybridization is customizing the properties to suit the requirements of applications. Many researchers [2]–[4] are mutually agreed that hybrid composites are capable of providing a mix of ductility, stiffness, as well as strength that is not possible with a single fibre reinforcement composite. Recently, researchers have begun to explore hybrid composite systems using different manufacturing techniques. The stack configuration is one of the most widely investigated techniques [5], [6].

The fabric stacking strategy allows the researcher to design the material sequence according to the specific requirements for the desired material thickness and strength performance. Researchers commonly practiced

two stacking approaches; stacking different type of fibers or weave structures within a single composite matrix. For example, a scientific work [6] studied woven composites' impact behaviour at low velocities using three fibre types – glass (G), carbon (C) and basalt (B). The layering sequence of woven composites developed in the study is based on CBGBC and BGCGB. Both types of hybrid composites were made with 16 layers and thickness of 3.8 mm. The outcome shows that utilizing carbon in the middle layer sequence did not yield the same level of performance as placing carbon in the outer layer. Meanwhile, according to a scientific literature [7], the arrangement of the hybrid fabric stacking sequence between low-performance fiber and carbon woven fabric significantly influences tensile and bending strengths. Researchers are able to improve the flexural and tensile strength performance with respect to composite structures and reduce bending crack damage by arranging carbon-woven fabric layers at the bottom of the sequence rather than assembling them alternately with glass-woven fabric. Besides that, scientific studies [8], [9] also reported a consistent outcome on the hybrid woven composite stacking arrangement between carbon and glass fiber woven fabrics. The fabric stacking setup of carbon fabric at the outermost layer substantially enhanced stiffness and impacted cracking failure behavior. These research works showed that modifying hybrid materials can lower material costs while strengthening bending and impact load-displacement performance. It can be estimated that the successful development of hybrid carbon-glass woven composite by incorporating more ratio of glass fiber will significantly reduce the material cost ranging from 25 – 60 % while maintaining a good mechanical strength performance.

Besides on stacking different type of fibers within a single composite matrix, many researchers also enticed the utilization of different weave structures combine together within a single composite matrix. Previously, several literatures have reported the use of two different types of weave structures within a single composite matrix. For instance, a study [10] investigated the role of combining two weave structures with different yarn float length configurations. The e-glass woven fabrics were manufactured into satin and plain weaves. The three-ply hybrid woven composite was developed with six distinctive stack configuration parameters. Researchers have identified that positioning weave structures with longer yarn float lengths at the top layer significantly contributes to better flexural results. This is because a satin weave structure is able to provide higher maximum flexural stress resistance than a plain weave. Meanwhile, positioning plain weaves at the top layer will provide an advantage for tensile strength. This is because plain weave exhibits better tensile strength performance. In the meantime, another study [11] worked on a hybrid woven composite for quasi-static tensile loading analysis. Two different hybrid stack configuration systems were developed based on plain weave e-glass fabric as well as satin weave carbon fabric. The results showed that adding glass layers to the exterior outperforms adding carbon layers in terms of tensile strength. Researchers have identified that this occurrence happens because the glass plain weave layers have more tensile strain than carbon satin weave layers. Therefore, the surrounding glass layers limit the potential progression of damage in carbon layers. Consequently, carbon layers in the G₃C₃G₃C₂ configuration could take more strain before failure. Similarly, a group of scientist [9] also adopted a similar stack technique for hybrid woven composite analysis. The hybrid glass Kevlar woven composite was developed using four stack approaches. The glass (G) woven fabrics are in the form of plain weave, while the Kevlar (K) fabrics are in the form of twill weave. The findings revealed that G₅K₁₀G₅ produced the best low-velocity impact performance. Moreover, it has been observed that positioning glass at the exterior layer while Kevlar at the interior section yielded better composite stiffness performance. Researchers have determined that the impact load was majorly transferred to the Kevlar fabric because of its capability to absorb more impact load than glass fabric.

It is well established that hybridization of carbon and glass positively will improve the mechanical tensile of hybrid composite. However, stacking different weave structure at the top and at the bottom section of hybrid composites may alter mechanical tensile performance due to the uneven stress distribution. Therefore, it sparks an interest to characterize the hybrid carbon/glass woven composites configured by using different stacking strategies. In this study, the woven fabric samples were examined for physical characterization of crimp, and woven fabric density. Later, the woven fabric stacking strategies were introduced to develop a hybrid carbon/glass woven composites by incorporating different weave structures. The hybrid woven composites are then tested for the mechanical tensile strength test. All scientific works done were performed according to the ASTM procedures.

2. Material and Methods

All woven fabric samples were sourced from CST The Composite Store Inc., located in California, USA. In general, the woven fabric samples can be classified into four different types: carbon plain (CP), glass plain (GP), glass twill (GT), and glass satin (GS). Figure 1 presents the woven fabric samples employed in the study.

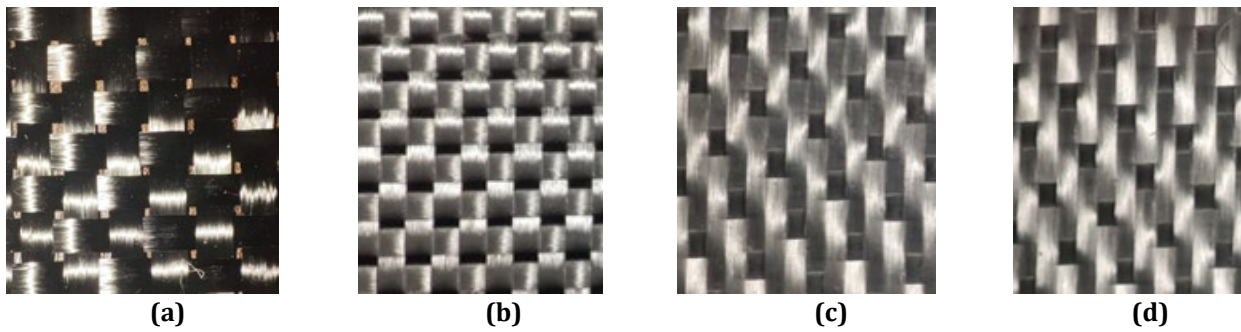


Fig. 1 Woven fabrics used in the study (a) Carbon plain; (b) Glass plain; (c) Glass twill; and (d) Glass satin

Each woven fabric was constructed with unique yarn float lengths. The basic weave pattern consisted of one warp yarn floating over one weft yarn in the plain weave structure. In contrast, the twill weave structure involved four warp yarns floating over one weft yarn, and the satin weave structure featured seven warp yarns floating over one weft yarn. Specifics regarding the woven fabric samples weave structure utilized in the study can be found in Table 1. Meanwhile, the woven fabric physical properties can be found in Table 2.

Table 1 Weave structure configuration

No.	Fiber Type	Weave Structure	Yarn Float Length	Acronym
1	Carbon	Plain	1/1	CP
2	Glass	Plain	1/1	GP
3	Glass	Twill	4/1	GT
4	Glass	Satin	7/1	GS

Table 2 Woven fabric physical properties

No.	Acronym	Warp Crimp (%)	Weft Crimp (%)	Number of Ends (per cm)	Number of Picks (per cm)
1	CP	0.80	0.80	7	7
2	GP	2.13	2.07	20	20
3	GT	3.39	3.39	31	31
4	GS	3.93	3.93	31	32

Hand lay-up method was used to fabricate the hybrid woven composites. Before that, the woven fabrics were stacked together 8 layers with different configurations. The stacking configurations were presented in Table 3. The composite fabrication procedure began with the preparation of woven fabric samples cut into 25 cm (length) x 25 cm (width) dimensions. In the study, BJC 39 epoxy resin Part A and B was mixed together with ratio of 37:113 for every 50 g of epoxy solutions. A 1.6 kg amounts of weight pressure were applied to the wetted woven fabrics. Then, the wetted woven fabrics were cured at room temperature, 23°C, for 8 hours. Afterward, woven composites were cut using a vertical bandsaw according to the sample dimension required for further characterization.

Table 3 Hybrid woven composite stacking sequences

		Reference Code	A	B	C	D	E	F	G	H
Position	Top Surface	1	CP	GS	GT	GP	GS	GT	GP	CP
		2	GP	CP	GS	GT	CP	GS	GT	GP
		3	GT	GP	CP	GS	CP	GS	GT	GP
	Middle Layer	4	GS	GT	GP	CP	GP	CP	GS	GT
		5	CP	GS	GT	GP	GP	CP	GS	GT
		6	GP	CP	GS	GT	GT	GP	CP	GS
		7	GT	GP	CP	GS	GT	GP	CP	GS
	Bottom Surface	8	GS	GT	GP	CP	GS	GT	GP	CP

Woven composite tensile reflects the woven composite strength capability to deform under tensile loading before it starts to break. The woven composite tensile test measures the maximum stress per cross-sectional area in the units of MPa, strain elongation in the units of %, and tensile modulus in the units of GPa. The test was conducted based on the ASTM D638 standard using a Bluehill Instron universal testing machine. The load cell and crosshead speed were set at 50 kN and 2 mm/min, respectively. The woven composite sample size was prepared at 20 cm (length) x 2.5 cm (width).

The maximum tensile stress, tensile strain, and tensile modulus were measured based on Equations 1, 2 and 3, respectively. In equation 1, the maximum tensile stress, σ is measured by the maximum load produced, F divided by the cross-sectional area of the composite sample, A . The outcome of the tensile stress was assessed in units of megapascals (MPa).

$$\text{Tensile Stress } (\sigma) = \frac{F}{A} \tag{1}$$

In equation 2, the maximum tensile strain, ϵ represents the product of extended length ΔL and the original length of the composite sample, L . The tensile strain result was measured in percentage units.

$$\text{Tensile Strain } (\epsilon) = \frac{\Delta L}{L} \tag{2}$$

Meanwhile in equation 3, the tensile modulus, E measured the upper and lower regions of tensile stress and strain at the linear line. The tensile modulus result was measured in megapascals (MPa) units.

$$\text{Tensile Modulus } (E) = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1} \tag{3}$$

3. Result and Discussions

3.1 Tensile Strength

Extensive evaluation was made to compare the current hybrid woven composite tensile strength with the single glass and carbon fiber woven composites. Figures 2 and 3 presented the assessment of tensile strength in the warp and weft directions. Additionally, the charts were also divided according to three benchmark regions based on the single fiber woven composites' tensile strength and tensile modulus results. It was established that CP-woven composite tensile results constantly produced the highest outcome. Therefore, CP woven composite was identified as the highest benchmark. Later, the middle and lowest benchmark regions were determined according to the GP, GT, and GS tensile performances.

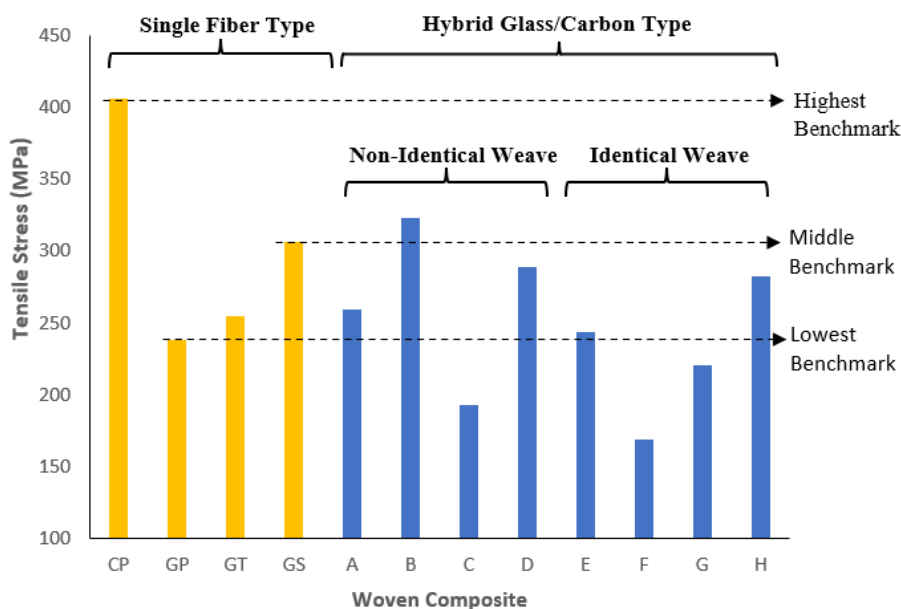


Fig. 2 Uniaxial tensile stress performance of single glass, single carbon and hybrid glass/carbon woven composites at warp direction

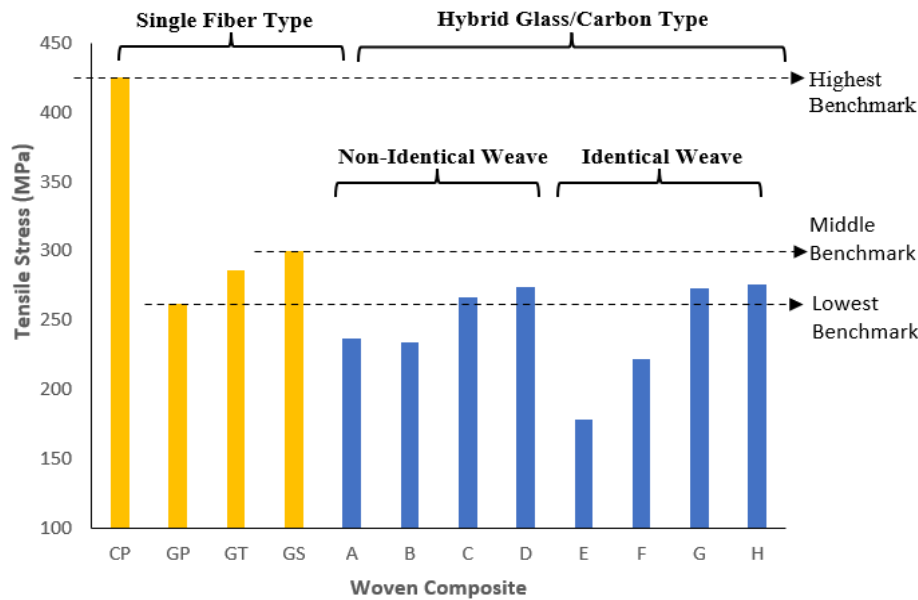


Fig. 3 Uniaxial tensile stress performance of single glass, single carbon and hybrid glass/carbon woven composites at weft direction

Three different tensile strength standard levels were identified to be used as the benchmark in this evaluation. The benchmark level was identified based on the single fiber woven composite tensile strength performance in the warp and weft directions. The benchmark level was ranked as highest, middle, and lowest. In this case, carbon fibers were classified as the highest benchmark performance. Meanwhile, the middle benchmark level was established, rendering to the GS woven composite tensile strength, and the lowest benchmark level was determined corresponding to the GP woven composite tensile strength.

Based on both Figure 2, and 3, it can be observed that the use of different weave structure approach on stacking arrangement yielded inconsistent tensile strength results between warp and weft directions. In the warp direction case, only hybrid B tensile strength passed the middle benchmark performance. On the contrary, hybrid A, D, E and F sequences could only concede the lowest benchmark level, as illustrated in Figure 2. Unlike the warp direction, neither hybrid woven composite in the weft direction reached the middle benchmark level, as depicted in Figure 3. Besides, only hybrid C, D, G, and H woven composites have bypassed the lowest benchmark. Therefore, it can be assessed that only hybrid D and H woven composites were consistently surpassed the glass fibers lower limit tensile strength performance in the warp and weft directions. The consistent tensile strength performance on hybrid D and H are mostly due to the configuration of plain weave structure placed at the top and bottom layers within the hybrid composite matrix. In contrast, only the hybrid F woven composite configuration had consistently failed to exceed the lowest benchmark in the warp and weft directions. This situation clearly proved that F stacking arrangement for both warp and weft directions had negatively reduced the tensile strength to a lower-level single fiber woven composites. The low tensile strength performance condition is due to the arrangement of glass fibers at the outer layers while the carbon fibers were positioned at the internal layer.

These findings strongly suggested that the incorporation of carbon fibre (CP) woven composite within the stacked hybrid carbon/glass fabrics arrangement was only capable of surpassing the glass fibre woven composites' tensile strength performance. This is because the combination ratio used to develop the eight-layer hybrid woven composite between carbon and glass fibers are 2 and 6 layers, respectively. Consequently, the hybrid carbon/glass woven composite's tensile strength was still strongly associated with the glass fibre woven composite behaviour. Nevertheless, adopting carbon fabrics within the hybrid woven composite system still improves the tensile strength performance through the stacking arrangement sequence.

3.2 Effect of Different Weave Structure Arrangements at the Outermost Layers

Later, the impact of various weave structures on the top and bottom surfaces of woven composites on the mechanical tensile strength property in the warp and weft directions is thoroughly examined. Figure 5 displays the woven fabrics stacking configuration used to develop the hybrid woven composite. Two different designs were introduced to fill the top and bottom surfaces of woven composite, identical and non-identical weave patterns. In the non-identical weave structure placement approach, hybrid A, B, C and D were developed by using various weave patterns at the top as well as bottom layers of woven composite. Meanwhile, in the identical

weave design attempt, hybrid E, F, G and H were built with a similar weave configuration at the top and bottom levels.

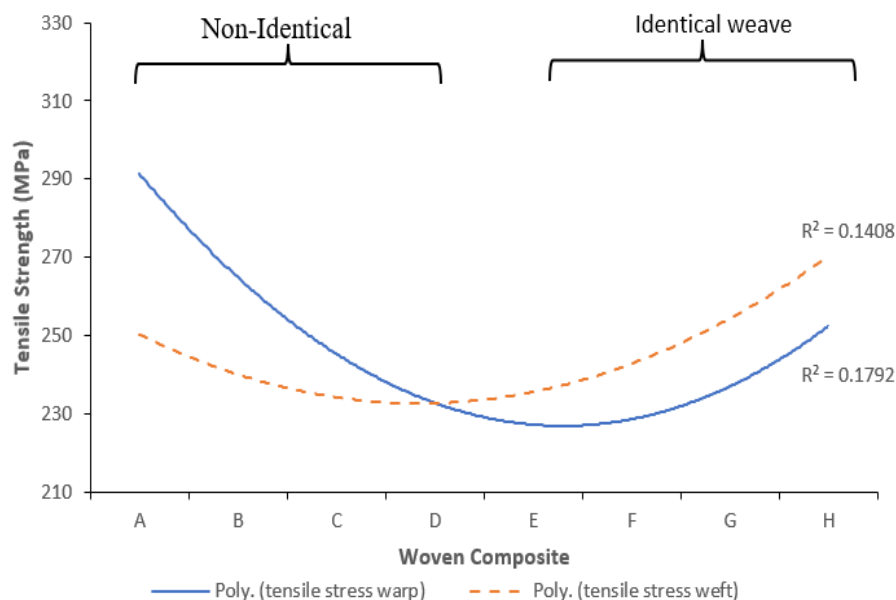


Fig. 5 Relationship between tensile strength and different weave structures placement at the outer layer woven composite

The analysis attempts to investigate the relationship between the tensile strength performance in the warp and weft directions, as well as the influence of different patterns in the hybrid woven composite. In general, the placement utilization of different weave structures on the woven composite outer layer substantially affects the tensile strength result. Both warp and weft trendlines were recorded with r-square values of 0.1792 and 0.1408, respectively. Both trendlines have a low r-square value as only axis Y represents the tensile strength value, whereas axis X represents the hybrid woven composite sequences.

In the non-identical weave pattern strategy, both warp and weft trendlines show a descending movement from hybrid A to D. It was found that hybrid A and B arrangements provided better tensile strength than hybrid C and D. Adoption CP and GS woven composite at the outer layer sequence resulted to the tensile strength enhancement. In the meantime, both trendlines converged at the hybrid D pattern. The trendline intersection clearly implies that the warp and weft directions had the equally least contribution to the hybrid D tensile strength. Meanwhile, in the identical weave pattern method, both warp and weft trendlines exhibit an ascending movement from hybrid E to H. The finding indicates that utilization of similar plain weave structures at the top and bottom outer layer generates better tensile strength performance.

3.3 Image Analysis of Tensile Failure

The typical hybrid woven composite tensile failure behaviours of samples A, B, C, D, E, F, G, and H are depicted in Figure 6 for both warp and weft directions. In general, the external woven fabric layers exhibit fibre failure behaviour, while the internal woven fabric layers display delamination failure behaviour. This occurs as a result of tensile stress concentration build-up from the matrix surface to the internal layers of the woven fabric. It was observed that the tensile failure rupture produced two different types of breaks: perpendicular and non-perpendicular in the longitudinal direction. The uneven type of fibre failure break is caused by the various failure mechanisms within each hybrid woven configuration, which are based on different sets of weave structures and types of fibre.

For the perpendicular break pattern, positioning carbon fabrics at the outer layer or near the outer layer inclines the hybrid woven composites to yield a perpendicular break. Carbon fabrics require more tensile stress to break apart. This condition leads to more stress concentration build-up on the carbon fabric layers to break before the stress concentration spreads to the other layer [12], [13]. Meanwhile, for the non-perpendicular break pattern, positioning glass fabrics at the outer layer highly influences the hybrid woven composites to generate a non-perpendicular break. Glass fabrics require less tensile stress to break apart than carbon fabrics. Therefore, the initial stress concentration build-up on the glass fabric layers at the outer layer is low. However,

greater stress concentration build-up is needed to break the carbon fabrics at the internal layer. Hence, the uneven stress concentration distribution leads to a non-perpendicular break [12], [14], [15].

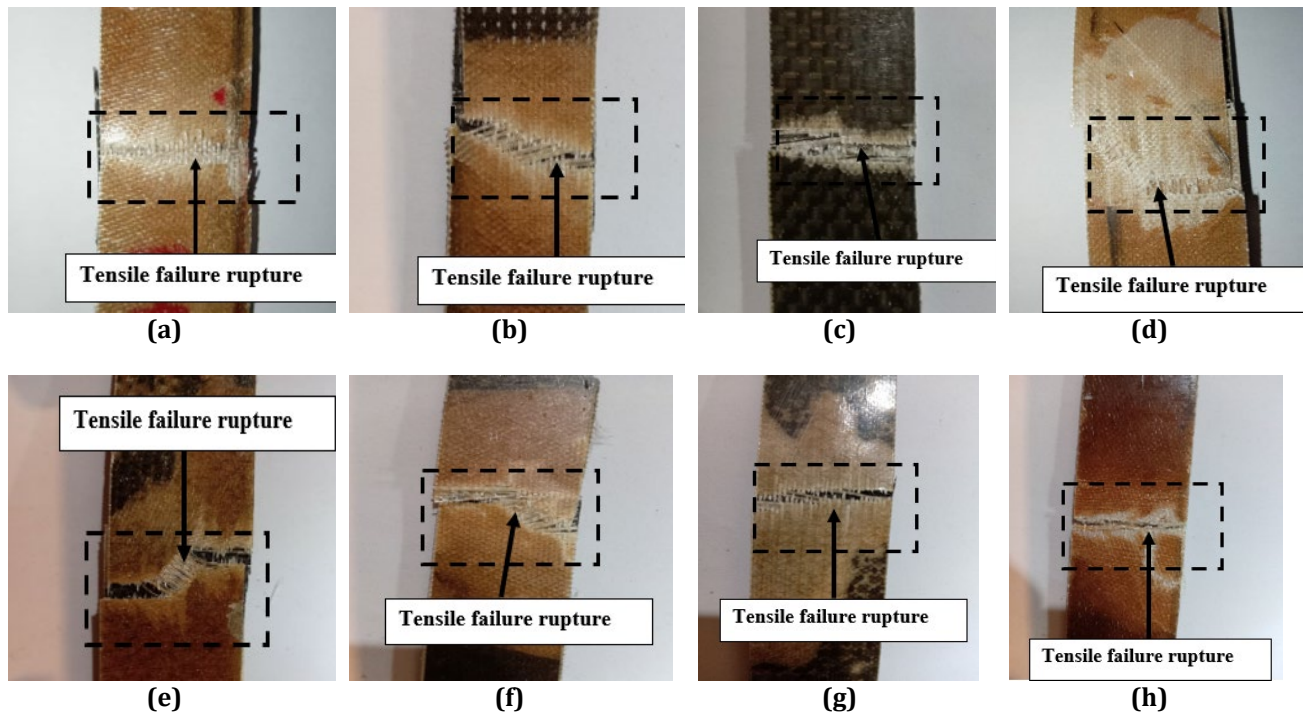


Fig. 6 Tensile failure rupture trends on hybrid glass/carbon woven composites (a) hybrid A; (b) hybrid B; (c) hybrid C; (d) hybrid D; (e) hybrid E; (f) hybrid F; (g) hybrid G; and (h) hybrid H configurations

4. Conclusion

An investigation was carried out on the mechanical strength performance of single carbon fiber, single glass fiber, as well as hybrid glass-carbon woven composite. The research work was designed to achieve the research objective, which was to evaluate the uniaxial tensile performance of single glass fiber, single carbon fiber, and hybrid glass/carbon woven composites based on the woven fabric stacking arrangement variations within a single composite matrix. The results of the experiment revealed that the fabric stack configuration significantly influenced the tensile strengths of the hybrid woven composites. The tensile strength evaluation revealed that hybrid B sequences recorded the highest tensile stress, averaging 322.75 MPa in the warp direction. On the other hand, hybrid F variations had the minimum tensile stress value with an average of 169 MPa. Furthermore, a comparison with single fiber composites indicated that hybrid B successfully surpassed 8-layer GS woven composites with 5.3% higher tensile strength. Overall, the hybrid woven composites demonstrated the ideal tensile strengths when utilizing a non-identical weave pattern configuration at the outermost layer. Nevertheless, the current hybrid glass/carbon woven composites tensile performance shows a promising outcome that can potentially be incorporated into technical applications. However, further improvements can be explored to optimize the existing hybrid glass/carbon woven composites tensile results to cater to the carbon plain woven composites tensile strength performance.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Author 1, and Author 2; **data collection:** Author 1; **analysis and interpretation of results:** Author 1, and Author 2; **draft manuscript**

preparation: Author 1, and Author 2. All authors reviewed the results and approved the final version of the manuscript.

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