Journal of Metals, Materials and Minerals, Vol. 31, No. 1, pp. 35-43, 2021

Improvement on cost-performance ratio of fiberglass/carbon fiber hybrid composite

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Received date:
6 January 2021
Revised date
9 February 2021
Accepted date:
13 February 2021

Keywords:
Cost-performance;
Hybrid Composite;
Carbon Fiber;
Fiberglass;
Tensile Properties

Abstract

Fiberglass composite (FG) is widely used as a metal substitute in general applications due to its corrosion and chemical resistance, relatively high strength, and low cost. Still, the FG is deficient in performance and relatively heavy for airframes. Carbon fiber composite (CF) is utilized instead as it has greater performance and lower weight. However, the CF is brittle and expensive. Thus, in this work, we combine FG and CF into two types of hybrid composites to achieve a cost-effective solution with greater or comparable mechanical properties to those of CF. The first one uses FG as core and CF as skins (SWFG). The second one uses CF as core and FG as skins (SWCF). Their mechanical properties and cost-performance ratios (CPR) are compared. The results show that the mechanical properties of the SWFG composite, especially the modulus of elasticity, are considerably improved over the FG and nearly match those of the CF. Also, the SWFG has better CPR regarding tensile properties and flexural modulus than the SWCF and the CF. The SWFG shows promising potential as an alternative to the CF due to its comparable performance and almost 40% lower cost than the CF.

1. Introduction

For decades, unmanned aerial vehicles (UAVs) have played an increasingly important role in national security and military-related operations, including non-traditional threat prevention and humanitarian assistance and disaster relief (HADR), owing to their superior functionality over humans. As a result, many countries and government agencies have been investing a huge amount of money, if not billions, to enhance the performance of UAVs even further. A crucial factor to improve the efficiency of UAVs is the development of their structural materials towards being stronger, lighter, more durable, and more environmentally friendly while lowering their costs.

The technology of airframe materials and their manufacturing processes have progressed considerably over the years [1]. Owing to their superior properties and potential for improvement, composite materials have been the number one choice material for aircraft structures. As a result, they have been continuously improving to achieve higher performance, particularly their mechanical properties such as strength and stiffness. Generally, aircraft structures made from composite materials have higher strength-to-weight ratios compared to conventional metal structures. The composite airframe has a very smooth surface and curves that reduce drag significantly. Unlike its metal counterpart, the composite airframe does not corrode and suffers less from fatigue. Further, the properties of composites can be easily modified to fit any requirements for any applications by combining different materials in different volume fractions and altering their mutual arrangement in a variety of ways [2-6].

The most common type of reinforcement used in polymer-based composites is glass fiber. The glass fiber reinforcement can be used in a variety of forms such as powder, woven roving, fabrics, chopped strand mats, etc. The fiberglass-reinforced polymer composite is mostly employed in a variety of general applications including bicycle, boat, RC toys, and small-medium UAV because it offers a range of advantages over traditional materials. For example, it provides relatively higher strength, light structural weight, corrosion resistance, and chemical resistance [7,8]. More importantly, it is remarkably inexpensive. Nevertheless, fiberglass composite is still inadequate when it comes to more demanding applications such as aerospace applications, which require a much higher strength-to-weight ratio, especially in tensile strength and stiffness because glass fibers possess relatively low tensile strength [9]. This is when carbon fibers come into play.

Carbon fibers, also known as graphite fibers, have a graphite-like structure which is made of carbon atoms connected in a hexagonal shape by sp^2 hybridization bonding forming horizontal layers. The commercially available carbon fibers can achieve as high as ~7 GPa in tensile strength and ~965 GPa in tensile modulus, depending on the type of their precursors and their configurations [10]. When utilized in a unidirectional configuration, the tensile strength and modulus of the carbon-fiber-reinforced polymer composite can achieve up to ~4 GPa and ~180 GPa, respectively [11]. Therefore, the carbon fiber composite has become the first of many choices in advanced sporting goods, race cars, aircraft, and even civil architectural structures. However, the shortcomings of carbon fibers do exist; they have relatively lower failure strain and have steep prices. Subsequently, scientists and engineers have shifted their interests towards a more advanced composite material known as hybrid composite.

The hybrid composite is essentially a composite that employs a combination of two or more reinforcements bound together in a common matrix. It can incorporate various kinds of reinforcements, whether natural [12-14] or synthetic fibers [15-17]. The intention is to enhance properties in certain areas but slightly compromise the performance in some areas—while in some cases lower the cost considerably. Although there have been plenty of studies on the fiberglass-/carbon fiber-reinforced hybrid composites with positive results on their mechanical properties improvement, most of them applied unidirectional fibers and rarely consider their costs against their performances [18-21].

Hence, in this work, we study the effects of combining a plain weave glass fiber and a plain weave carbon fiber in hybrid epoxy-based composites on tensile and flexural properties. The goal is to ascertain their cost-performance ratios and their potentials as alternative materials for the airframe.

2. Experimental

2.1 Materials and procedures

The reinforcements that we use for the fabrication of composites in this work are 200 $g \cdot m^{-2}$ plain weave glass fiber (E-glass) fabric and 205 $g \cdot m^{-2}$ 3k plain weave carbon fiber fabric, respectively. The fabrication technique is vacuum resin infusion with epoxy resin as the polymer matrix. To ensure the homogeneity of the fabricated specimens and the consistency of our fabrication technique, we examine the relationship between the thickness of the specimens and the number of reinforcement layers used. Figure 1 shows the thicknesses of the fabricated fiberglass and carbon fiber composites plotted as a function of their respective number of reinforcement layers along with linear fit lines. The plots clearly show a linear proportionality for both FG and CF specimens with the goodness of fit, χ^2, of 0.9997 and 0.9984, respectively. These calibration curves are used as a tool for controlling the thickness of composite specimens we want to fabricate by selecting a suitable number of reinforcement layers for each type.

2.2 Fabrication of composite specimens

We fabricate 4 different types of composites each with 2 sets of specimens for tensile and flexural properties testing—hence, 8 sets of composite specimens in total. The first and the second types are the conventional fiberglass-reinforced epoxy composite (FG) and carbon-fiber-reinforced epoxy composite (CF). The third type is a hybrid composite that has a sandwich panel structure fabricated by having fiberglass in the middle (core) sandwiched by carbon fiber on the outsides (skins). We call this composite "SWFG". The last type is also a sandwich structured hybrid composite similar to the SWFG but the carbon fiber is used as a core and the fiberglass is used as skins instead. We call this composite "SWCF". The specimens for tensile properties testing are fabricated in accordance with ASTM D3039, having a width of 20 mm, a length of 200 mm, and a thickness of 2 mm. For flexural properties testing, specimens are fabricated in accordance with ASTM D7264, having a width of 13 mm, length of 211.3 mm, and thickness of 4 mm. We choose a balanced structure for both types of specimens. For example, a specimen for flexural properties testing features 2 mm for core and 1 mm for each skin (2 mm in total). A flexural property test specimen features 1 mm for core and 0.5 mm for each skin (1 mm in total). For every type of specimens, each layer is placed at a 0° angle to each other. The number of reinforcement layers for skins or core for each type of composites is chosen based on their thicknesses. That is the skin or core needs to have an identical thickness across all types of composites so that the overall thickness of the specimen stays the same according to the standard test methods. For instance, in an SWFG specimen, its core is made of 12 layers of glass fiber fabric and its skin is made of 4 layers of carbon fiber fabric (8 layers in total). For an SWCF, its core is made of 7 layers of carbon fiber fabric and its skin is made of 6 layers of glass fiber fabric (12 layers in total). Table 1 and Table 2 describe the number of reinforcement layers and their arrangement for each type of composite specimen for tensile and flexural properties testing, respectively.

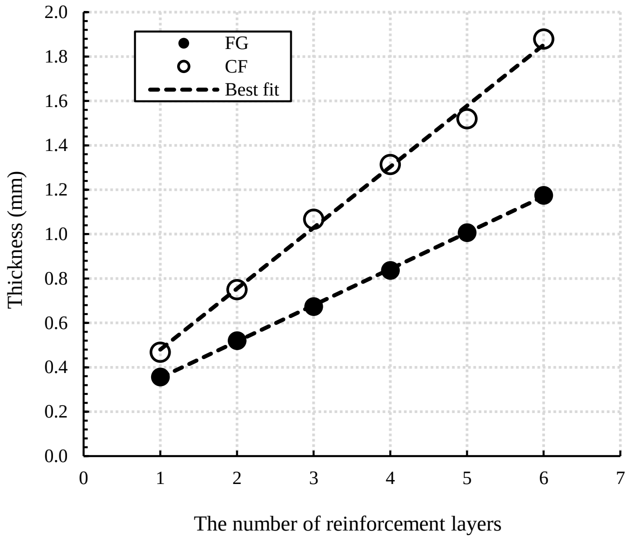

Figure 1. The thicknesses of the FG specimens (open circle) and the CF specimens (closed circle) plotted as a function of the numbers of reinforcement layers along with their respective best fit (dashed lines).

Table 1. The number of reinforcement layers and their arrangement for each type of composite specimens for tensile properties testing. The number of layers is chosen so that all types of specimens have a similar thickness of 2 mm.

Composite Type	Number of reinforcement layers					
	Top skin		Core		Bottom skin	
	FG	CF	FG	CF	FG	CF
FG	3	-	5	-	3	-
CF	-	2	-	3	-	2
SWFG	-	2	5	-	-	2
SWCF	3	-	-	3	3	-

Table 2. The number of reinforcement layers and their arrangement for each type of composite specimens for flexural properties testing. The number of layers is chosen so that all types of specimens have a similar thickness of 4 mm.

Composite Type	Number of reinforcement layers					
	Top skin		Core		Bottom skin	
	FG	CF	FG	CF	FG	CF
FG	6	-	12	-	6	-
CF	-	4	-	7	-	4
SWFG	-	4	12	-	-	4
SWCF	6	-	-	7	6	-

2.3 Mechanical properties characterization

The tensile properties testing is performed in compliance with ASTM D3039 using Instron 8801 universal testing machine. The speed of testing is 2 mm·min^{-1}. The specimens are tabbed by FR4 material so that the force is exerted on the center of the specimen—breaking at grip will be less frequent. We also use emery cloth to tighten the gripping to avoid specimen sliding off the grip jaws. The flexural properties testing is performed in compliance with ASTM D7264, procedure A. The speed of testing is 5 mm·min^{-1}. We use a span length of 176 mm which leads to a span-to-thickness ratio of 44:1. All specimens are given an increasing force and their corresponding stresses are recorded against their percent strain until broken. Some specimens can have multiple breaking points. The tests are stopped after the final break. The measurement is repeated five times for both types of testing. Only the strength, strain, and chord modulus properties are studied in this work.

3. Results and discussion

3.1 Tensile properties

The FG composite demonstrates more flexibility than the other composites. Though the specimens can be stretched to relatively high percent strain and their tensile stress-strain response is not perfectly linearly in the elastic region, the specimens break sharply without exhibiting plastic deformation beyond the maximum tensile stress as shown in Figure 2. The average values of tensile strength, tensile strain, and tensile chord modulus of all composite specimens are shown in Figure 3. The FG exhibits fairly low tensile strength with an average value of 388 MPa and has a rather high strain at break of 2.93%. Consequently, its tensile modulus of elasticity is the lowest with an average value of 18 GPa. Our results are in good agreement Ray *et al.* [22] where they reported the maximum tensile strength of 369 MPa for the woven fiberglass (E-glass) composite. Jafari *et al.* [23] reported lower tensile strength of 275.21 MPa but with a similar strain at break of ~2% and chord modulus of 17.845 GPa for the 2 mm woven E-glass composite tested at 25°C.

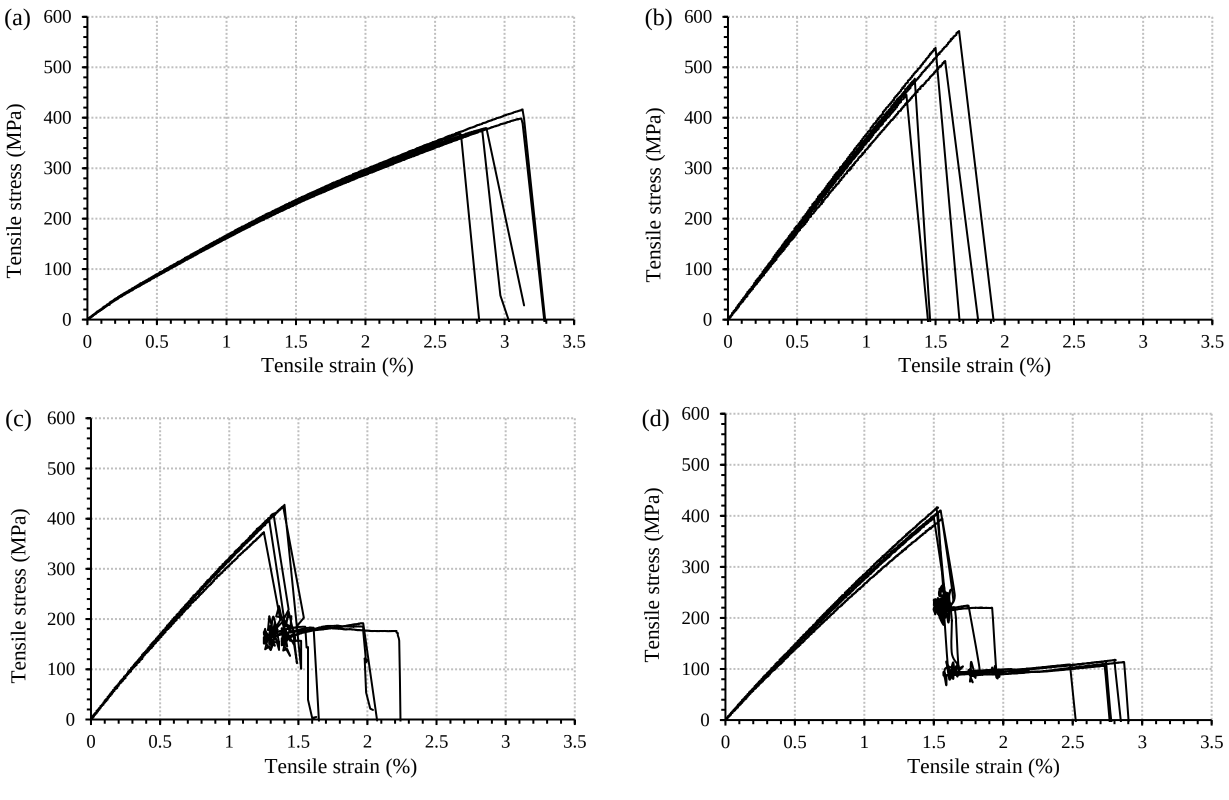

Figure 2. Tensile stresses of the (a) FG, (b) CF, (c) SWFG, and (d) SWCF composites plotted against their respective tensile strain. The measurements for each composite are repeated five times.

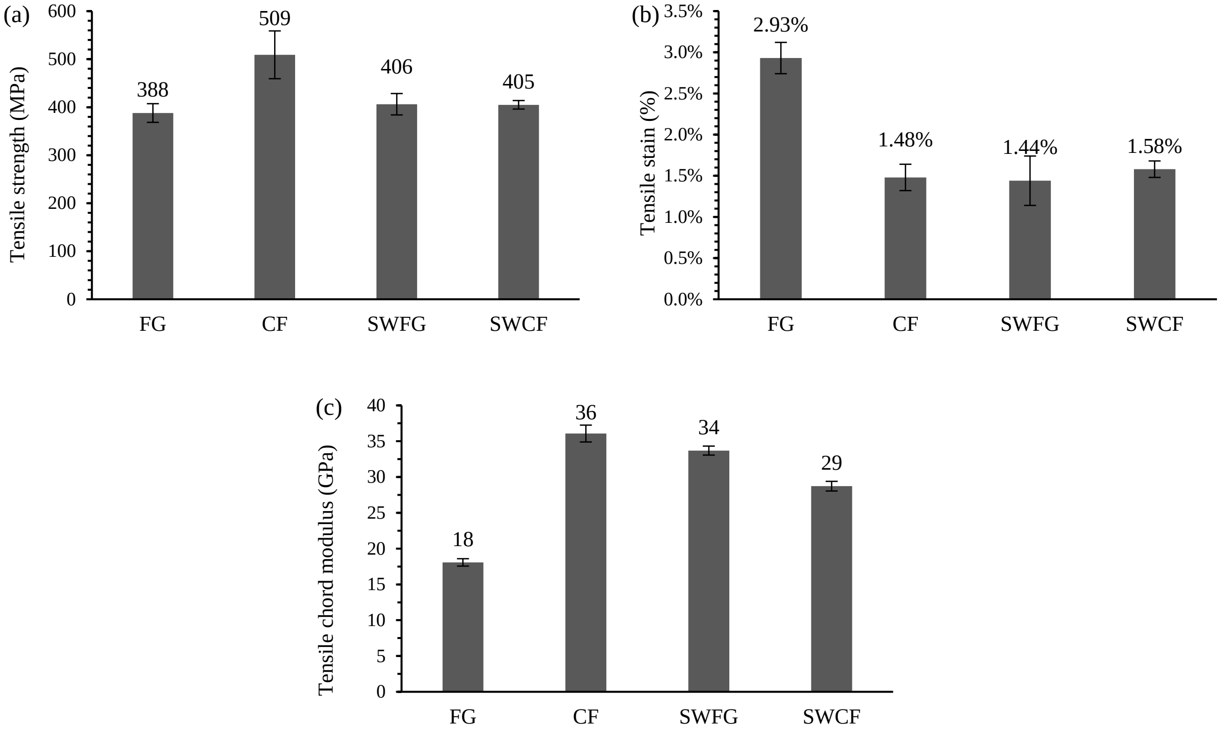

Figure 3. The comparison of the (a) tensile strength at break, (b) tensile strain at break, and (c) tensile chord modulus of FG, CF, SWFG, and SWCF composites.

The CF composite is less flexible than the FG composite. The CF exhibits a linear tensile stress-strain response in the elastic region and without plastic deformation. It has almost half percent strain at break of that of the FG with an average value of 1.48% but has a significantly higher strength with an average value of 509 MPa. Consequently, it has an average tensile modulus of 36 GPa, which is doubled that of the FG. Our values are in line with others. Jagannatha *et al.* [24] reported the ultimate tensile strength of the bi-directional woven carbon fiber composite of about 500 MPa. Eksi *et al.* [25] reported a much lower tensile strength of 340 MPa but with a higher modulus of 42 GPa resulting from a lower strain at break of 0.9%.

The stress-strain response of the SWFG composite is quite different from those of the FG and CF. Overall, it combines the properties of both FG and CF. The stress-strain curves feature two breaking points. It has a linear stress-strain response in the elastic deformation region and low strain at break similar to that of the CF which is 1.44%. It has however tensile strength close to that of the FG with an average value of 406 MPa. As a result, it has a high tensile modulus of 34 GPa, which is comparable to that of CF. The first break corresponds to the breaking of the CF skins. Then the delamination of the CF skins from the FG core occurs as shown in Figure 4. The CF skins around the broken area detach from the FG core. After that, the specimen breaks for a second time with a little higher percent strain than that of the first break. Our findings agree well with others in the literature.

The SWCF composite has similar behavior to the SWFG composite but unlike the SWFG, the SWCF has 3 breaking points. The maximum tensile strength is identical to the SWFG but with a slightly higher tensile strain of 1.58%. This results in a lower modulus of 29 GPa.

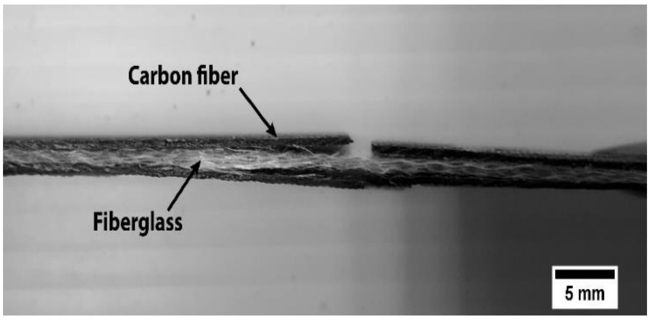

Figure 4. An example of a broken SWFG specimen after tensile properties testing. The delamination of the CF skins from the FG core around the broken area is clearly shown. The CF skins split apart after break whereas the FG core is still intact.

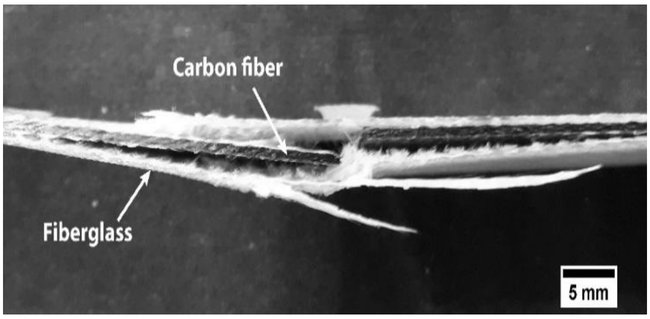

Figure 5. An example of a broken SWCF specimen after tensile properties testing. The specimen shows delamination of the FG skins from the CF core around the broken area. The CF core splits apart after break whereas the FG skins do not.

Similar to the SWFG, the first break results from the breaking of the CF core. Immediately after the first break, another follows at a percent strain not far from the first. The FG skins then continue to receive the load for a short while, stretch further, and finally break at around 2.75% strain. The final break results in an explosive tear of the FG skins but does not split completely as does the CF as shown in Figure 5.

In comparison, the FG has the lowest tensile strength and modulus. The CF has the highest tensile strength and modulus which are about 31% and 100% higher than the FG, respectively. Though the hybrid composites do not show obvious improvement on tensile strength over the FG, owing to their lower failure strain, their moduli improve drastically by 89% and 61%, respectively, compared to the FG. The behavior of these hybrid composites is due to the fact that the FG and CF layers are being pulled in parallel analogous to springs with different spring constants connected in parallel are being pulled. The load was not shared equally in both springs but the elongation is. The stiffer spring receives more share of load than the other. Therefore, in the case of SWFG, the stress more concentrates on the CF resulting in a slightly higher tensile strength. However, the CF is more brittle or has a lower strain at break than the FG. Thus, the CF breaks before the FG. This leaves only the FG for receiving the load. As the FG continues to be stretched, the delamination occurs and finally fails at a later time. The reason the FG fails at a lower stress than that of the pure FG is that, in this case, the FG is thinner. Also, the deformation is no longer elastic and the spring analogy is not fully realized, so the failure strain is lower as well. In the case of SWCF, a similar explanation can be applied. The first break is due to the lower failure strain of the CF core. The load is now carried by the FG skins. A second break could be from a combination of the delamination and an initial crack of the FG because the stress level is equivalent to the second break of the SWFG. However, this time the FG of each is thinner and separated from each other on the sides, not in the middle. Hence, loads are less concentrated on each FG ply resulting in lower stress at the final break and also at higher strain.

Our observation is in line with Manders *et al.* [26] that a progressive failure is observed in FG and the addition of the CF component results in a more catastrophic failure along with delamination between FG and CF plies. A multiple cracking mode is present in the FG/CF hybrid composite due to initial fracture of CF, delamination crack, and transfer of the load to FG after the failure of the CF. The initial stiffness of the hybrid composite is improved as the CF content increases. Similar trends were also reported by Tabrizi *et al.* [27] for unidirectional FG/CF hybrid composites. Their pure CF composite (CF_8) yields the highest tensile strength and chord modulus of about 1200 MPa and 150 GPa, respectively, whereas the pure FG composite (FG_8) has the lowest tensile strength and chord modulus of about 800 MPa and 40 GPa, respectively. Their SWFG ($CF_1/FG_4/CF_1$) and SWCF ($FG_2/CF_2/FG_2$) composites show similar strength, modulus, and even strain at failure. The tensile strength of their SWFG and SWCF are about 900 MPa and 850 MPa, respectively, with the same chord modulus of about 70 GPa. Thus, their hybrid composites have around 12.5% improvement on tensile strength and around 75% improvement on modulus over the FG.

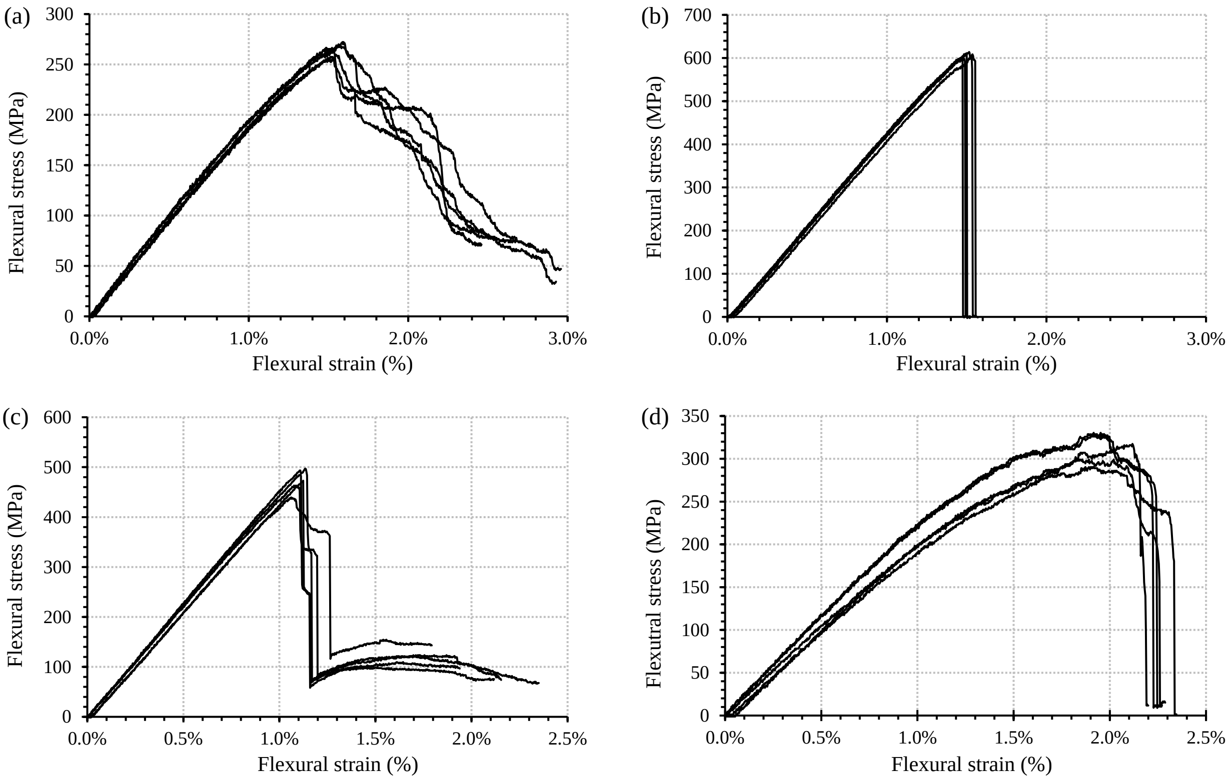

Figure 6. Flexural stresses of the (a) FG, (b) CF, (c) SWFG, and (d) SWCF composites plotted against their respective flexural strain. The measurements for each composite are repeated five times.

3.2 Flexural properties

The FG composite demonstrates considerably low strength than in the tensile case with an average value of 264 MPa as shown in Figure 6. The average values of flexural strength, flexural strain, and flexural chord modulus of all composite types are shown in Figure 7. The FG has a rather low flexural strain at break of about 1.55%. Thus, the flexural modulus is as low as 20 GPa. The specimens do not break apart and the stress gradually lowers over time. Comparing to the literature, our values are in good agreement. For example, Jagannatha *et al*. [28] reported a slightly lower flexural strength of about 200 MPa but with a similar modulus just under 20 GPa.

The CF has much higher flexural strength at 607 MPa but has a comparable strain at break of 1.50%. This makes the CF very stiff with the flexural modulus of 42 GPa but at the same time super fragile. It has a linear stress-strain response without a plastic deformation region. When breaks, the specimens split apart violently. Our values are in good agreement with other work in the literature. For instance, Jagannatha *et al.* [28] reported almost 600 MPa for flexural strength but with a slightly higher modulus of nearly 50 GPa.

The SWFG demonstrates a more interesting stress-strain response. The specimen can break up to 2 times. The maximum flexural stress is 471 MPa but the maximum strain is 1.10%. This results in a high modulus of 44 GPa which is equivalent to that of the CF. Unlike the CF, the SWFG specimen is still intact after the break and bends further without separating into two pieces. So, the measurement has to be stopped when the percent strain reaches beyond the 2% strain limit according to the standard test method. Immediately after the first break, another follows at a percent strain not far from the first. Then the stress goes up slightly and down again to the previous level at 2% strain. This suggests that the FG core is still receiving a load in shear and the buckling up of the broken top CF skin against the folding direction due to compression as shown in Figure 8 may also contribute slightly to the increase in stress as well. This failure behavior can be beneficial in practical use as the first crack can give an indication for a replacement and the part can still hold itself after the ultimate failure.

The SWCF is quite ductile than the others. Its stress-strain curve is evidently not so linear and also has a small plastic deformation behavior at the end. It has a relatively low maximum flexural strength of 314 MPa but still 19 % higher than that of the FG. Also, it has a large maximum percent strain of 1.93% and breaks at 2.23% strain. This gives it a low flexural modulus of 22 GPa.

In comparison, the FG has the lowest flexural strength and modulus. The CF has the highest flexural strength and modulus which are about 130% and 110% higher than the FG, respectively. The higher performance of CF over FG is due to their inherent properties in which the carbon fiber is much stronger and stiffer than the glass fiber. Moreover, the interfacial bonding to the epoxy is better in the case of the carbon fiber than in glass fiber [29]. These reasons also apply to the tensile properties as well. The flexural modulus of the SWFG is marginally higher than that of the CF composite but its flexural strength is roughly 22% lower. The SWCF composite does not perform as well as the SWFG. It demonstrates only a slight improvement over the FG composite in terms of flexural strength but has the flexural modulus equivalent to that of the FG. The characteristics of the SWCF leans towards the FG because, typically, a specimen under a flexural load receives tension on the bottom surface, compression on the top surface, and shear in the middle. This implies that the flexural properties of the specimens depend primarily on the tensile properties of the skins [30,31]. As a result, the SWFG has higher flexural strength and modulus than those of the SWCF because the FG has a lower tensile strength and modulus than the CF.

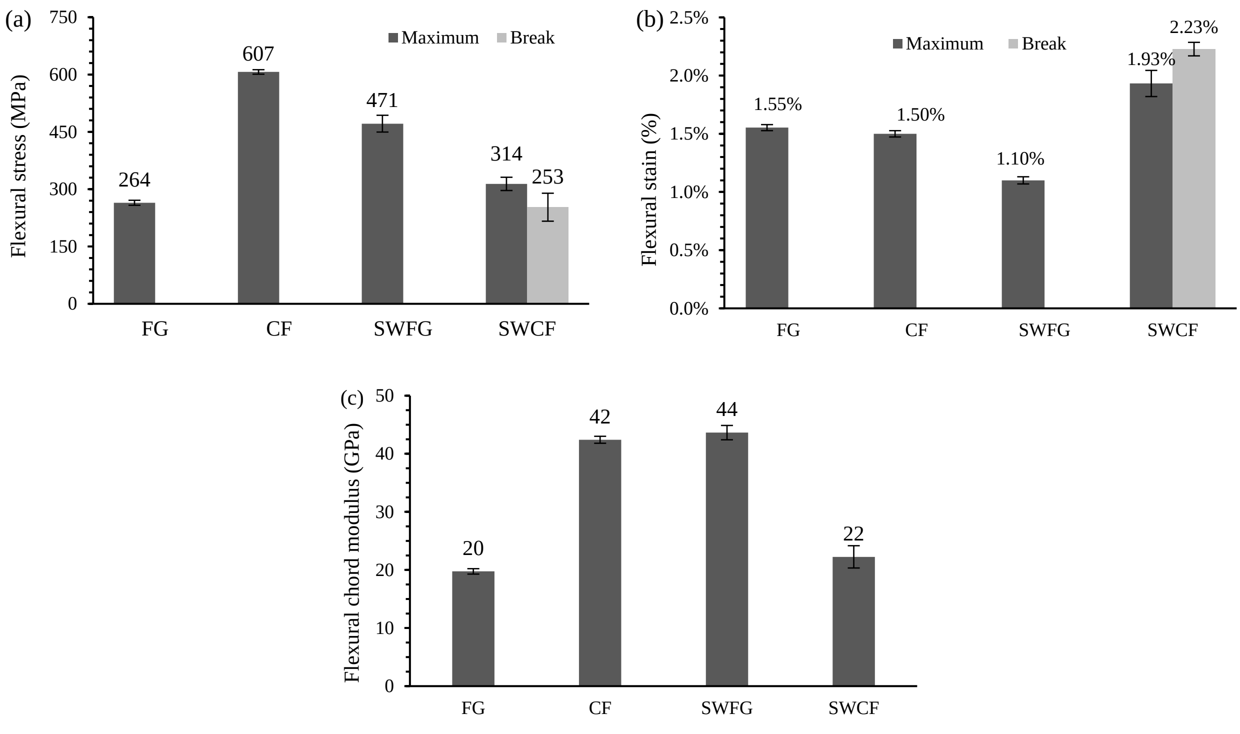

Figure 7. The comparison of the (a) flexural strength, (b) flexural strain, and (c) flexural chord modulus of FG, CF, SWFG, and SWCF composites. Due to a more flexible nature compared to the others, the SWCF contains maximum and break values.

Figure 8. An example of a broken SWFG specimen after flexural properties testing. The upper carbon fiber skin buckles up against the folding direction due to compression.

Similar findings were reported by Prusty *et al.* [32] on both the flexural properties and the failure behavior of the FG/CF hybrid composite. They found that placing CF on the bottom side leads to higher strength and modulus and a catastrophic failure whereas placing CF on the top side leads to progressive failure similar to the FG. Also, using CF as skins ($CF_2/FG_3/CF_2$) results in 4% and 7% lower strength and modulus, respectively, than those of pure CF composite whereas using FG as skins ($FG_1/CF_5/FG_1$) results in 10 % and 17% higher strength and modulus, respectively, than those of pure FG composite.

3.3 Cost-performance ratio

The characteristic of the material is not the only factor that is crucial to the material selection process for the construction of the airframe. The cost of material and material processing is also an equally important factor. Necessary compromises between cost and performance have to be made regularly. To ascertain the potential of the hybrid composites as alternative materials for airframe, we compare the performance, i.e., tensile and flexural properties, and the cost of the reinforcement for each composite, excluding epoxy resin and other costs involved in the fabrication processes as shown in Table 3.

The cost for each composite is calculated based on the amount of reinforcement used to fabricate a 1 m^2 × 4 mm thick specimen. The prices of the reinforcements are according to our supplier in Thailand [33].

We then use the information in Table 3 to determine the cost-performance ratio *(CPR)* for each composite, which is their performances *(P)* in each category over their costs *(C)* as in the following equation:

$$CPR = \frac{P}{C}$$

In this work, we only consider strength and modulus. The comparison of the cost-performance ratios for the composites are shown in Figure 9. Although the FG has the lowest performance of all, the price is extremely low. As a result, it is the most cost-effective choice for nearly all general applications. However, when higher performance and lower weight are needed, the CF is more suitable even if it has the lowest cost-performance ratio. The SWFG is better than the CF in terms of tensile modulus and flexural modulus while the SWCF is only better in tensile modulus. Similar results on the cost-performance by Chen *et al.* [34] have also been reported that the unidirectional hybrid composite ($CF_2/FG_4/CF_2$) showed the highest cost efficiency over other stacking sequences regarding flexural strength and modulus.

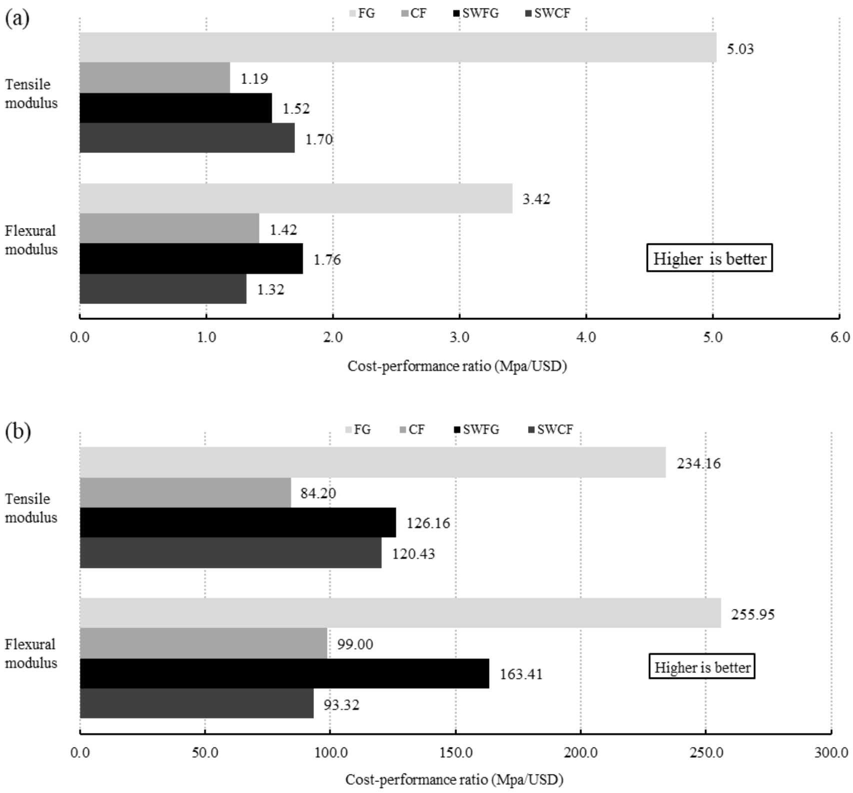

Figure 9. Cost-performance ratios of the FG, CF, SWFG, and SWCF composites regarding (a) tensile and flexural strengths, and (b) tensile and flexural modulus.

Table 3. Mechanical properties and costs for fabricating a 1 m^2 × 4 mm thick specimen of different types of composites**.**

Composite type	**FG**	**CF**	**SWFG**	**SWCF**
Tensile Properties				
Strength (MPa)	388	509	406	405
Strain	2.93 %	1.48 %	1.44 %	1.58 %
Modulus (MPa)	18,073	36,070	33,691	28,722
Flexural Properties				
Strength (MPa)	264	607	471	314
Strain	1.55 %	1.50 %	1.10 %	1.93 %
Modulus (MPa)	19,755	42,410	43,640	22,257
Cost* (USD)	77.18	428.37	267.05	238.50

*Estimated price on 20 September 2020

4. Conclusions

We have fabricated two types of hybrid fiberglass/carbon fiber reinforced composites, namely SWFG and SWCF, to study their tensile and flexural properties and investigate their cost-performance ratio compared to that of the FG and CF composites. The SWFG is structured by having fiberglass as a core and carbon fiber as skins, and vice versa for the SWCF. The SWFG composite exhibits the most enhanced mechanical properties with respect to the FG. Its modulus of elasticity is comparable to that of CF in both tensile and flexural and is tremendously higher than that of FG composite. Furthermore, we also determine the cost-performance ratios for each composite. The FG shows the best cost-performance ratio while the CF has the lowest value. Even though the FG has the highest cost-performance ratio, it cannot perform well in applications requiring high tensile and flexural moduli which the CF can offer. Nevertheless, the SWFG shows a better cost-performance ratio in tensile and flexural modulus than the SWCF and the CF. Hence, it could become an alternative material to CF as it gives a similar performance but with an almost 40% cost reduction.

Acknowledgements

We would like to express our gratitude to Asst.Prof. Gp. Capt. Sansanee Haemakom, Asst.Prof. Gp. Capt. Somkid Rahong, Assoc.Prof. Gp. Capt. Somkiat Sukanghong, and Prof. Gp. Capt. Kusaya Suvanvihok for helpful support. This work is funded by the Royal Thai Air Force.

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