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Experimental Investigation on the Mechanical Properties of Dactyl-Inspired Fiber-Metal Laminates with Glass Fiber

Rizuanul Arefin Emon[1,], Zarin Rahman Tapti[1], Mushfique Azad Takin[2], Md. Shariful Islam[1], Arup Kumar Debnath[1]*

[1]Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH
[2] Department of Materials Science and Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

ABSTRACT
The dactyl club of mantis shrimps has a periodic region with extraordinary mechanical properties, due to a helical structure made up of mineralized fibers. It has been established that composites made of a similar structure by rearranging the fiber orientation increase the performance characteristics of composites. In this paper, a dactyl-inspired unidirectional glass fiber-reinforced plastic fiber-metal laminate (UGFRP FML) is developed and its tensile and impact-resistant characteristics have been discussed. The tensile properties of UGFRP FML have been compared with two types of thermoplastic fiber metal laminates (TFMLs) that are self-reinforced polypropylene (Al/Curv) and glass fiber-reinforced polypropylene (Al/Twintex) TFMLs and the impact properties compared with two types of GLARE samples. It has been found that the tensile strength of UGFRP FML (120.337 MPa) is 140.5% and 119.92% less than that of the Al/Curv (265 MPa) and Al/Twintex (290 MPa) whereas the maximum elongation of UGFRP FML is 5.61% less than Al/Curv and 0.22% more than Al/Twintex. The energy absorption capability of the UGFRP FML (61.67 J) has been found 25.86% and 137.19% more than that of the two types of GLARE specimens. The findings exhibit that the dactyl configuration of glass fiber in the composite is a successful method of enhancing FML's elongation to failure and impact resistance.

Keywords: Dactyl structure, Glass fiber, FML, Tensile properties, Impact resistance.

1. Introduction

Fiber-reinforced polymers (FRPs) are ideal for use in the building, automotive, marine, sports equipment, aerospace, and renewable energy industries because of their high tensile strength, lightweight nature, corrosion resistance, and design flexibility [1, 2]. Despite their benefits, FRPs are susceptible to delamination under impact and have brittleness, fatigue resistance problems, lower tensile strength, and limited compressibility [3, 4]. These restrictions may narrow their use in certain high-stress engineering applications. To cope with such limitations, many possible lines of inquiry have been explored and developed. Overall, thanks to its attractive mechanical properties, fiber metal laminates (FMLs) are one of the most advanced materials.

FMLs are composite materials that consist of layers of metals such as aluminum or titanium and layers of fiber-reinforced plastics. FMLs combine the benefits of metals which are ductile and have impact strength and fiber-reinforced composites which provide strength [5]. They are extensively employed in aviation, automotive, maritime, and military sectors for use in components operating under high impacts and cyclic stresses while remaining light in weight. similar FMLs such as GLARE found in many aircraft nowadays come with unique energy absorbing and structural toughness capabilities [6, 7]. Their design has been evolving thanks to the optimization in the combinations of fiber-metal composition and fibers orientations among other advanced materials thus making it suitable for diverse kinds of highly competitive engineering applications.

Due to its phenomenal resistance to fatigue and tolerance to impact loads, GLARE (Glass Laminated Epoxy Reinforced Aluminum) is one of the frequently used FMLs in numerous applications [8, 9]. ARALL (Aramid-Reinforced Aluminum Laminate) is a lightweight yet very strong and high-impact resistant material that has predominately been used in ballistic armour and components of vehicles [10]. Although hybrid laminates using FML and ceramics or Kevlar have been introduced into ballistic protection applications for enhanced energy absorption and protection, CARALL (Carbon Reinforced Aluminum Laminate) has been generally used in racing cars due to its strength and weight [11].

The most recent research developments in FMLs have focused more on biomimetic designs and replacing conventional materials with modern components to enhance functionality [12–14]. Biomimetic design enhances the internal layering and fiber orientations of FMLs by optimizing certain natural structures, such as the bending properties of natural fibers and shell properties of deformability. This method enables superior mechanical features such as higher energy absorption, improved damage tolerance, and multi-functionality [15].

One such remarkable structure is the dactyl club of *Odontodactylus scyllarus* (commonly known as mantis shrimps) which can sustain forces of 500N and above [16]. Morphologically, the dactyl's flattened club-shaped tip can be quickly swung to deliver strong blows. It is a complex

*Corresponding Author Email Address: arefinemon12@gmail.com Published By: SciEn Publishing Group

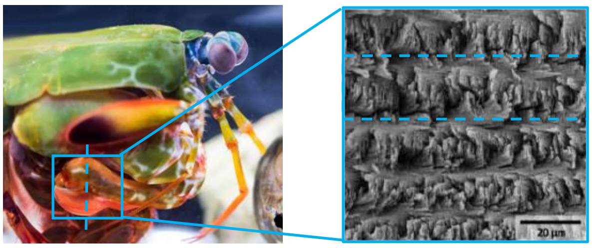
multi-layered structure in which the muscle fibers of the claw are arranged in a helicoidal pattern inside the chitin-based layer of the claw. This special arrangement of muscle fibers aids in impact force absorption and distribution, halting the spread of cracks through the material [17, 18].

Han et al. [19] studied the impact resistance of basalt fiber-reinforced aluminum FML and showed how the laminate arrangement improved the impact resistance compared to regular cross-ply [0°/90°] laminate, both experimentally and numerically. In another research, Han et al. [20] compared the impact energy absorption of helical fiber sinusoidal structure (HSL) to unidirectional fiber flat laminate (UFL) and helical fiber flat laminate (HFL) and showed how the HSL have better impact resistance compared to UFL and HFL, both experimentally and numerically. Moreover, Han et al. [21] compared the mechanical properties (tensile, compressive, flexural, hardness, and impact) of dactyl-inspired basalt fiber-reinforced sandwich composite (BFSC) to discontinuous basalt fiber-reinforced sandwich composite (DFSC). They concluded how the BFSC has improved mechanical properties than the DFSC. Shang et al. [22] also studied the effects of helicoidal-plies [0°/-18°/…/-180°] and [0°/-10°/…/-180°] arrangement of carbon fiber-reinforced sandwich structure. They found 34% increase in peak load compared to the conventional cross-ply sandwich structure.

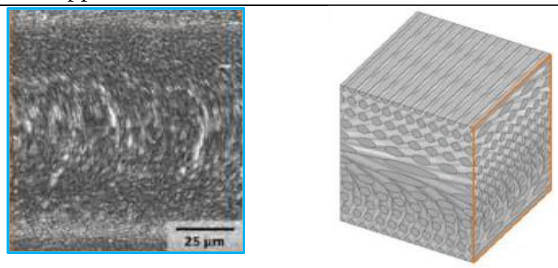
Although there have been several studies about the influence of dactyl structure on composite materials, there is no study about glass fiber reinforcement to make dactyl structure and the impact energy absorption capability using the Charpy impact test. In this work, a bioinspired FML has been designed and manufactured placing unidirectional glass fiber-reinforced plastic (UGFRP) between two aluminum sheets and through the hand layup method. The tensile properties of the produced FMLs have been compared with two types of thermoplastic fiber metal laminates (TFMLs) that are self-reinforced polypropylene (Al/Curv) and glass fiber-reinforced polypropylene (Al/Twintex) TFMLs from Ref. [4]. The impact resistance of the UGFRP FML has been compared with the GLARE-3 and GLARE-4 samples from Ref. [23].

2. The dactyl structure

The construction of the dactyl club begins with the composition of a soft framework made of chitin, which is cleverly arranged in a helical orientation shown in Fig. 1(a)-(d). Calcium compounds are then added to the club by the process of mineralization which results in a multi-layered helical structure shown in Fig. 1(b) and (c).



(a) (b)



(c) (d)

Fig. 1 (a) Dactyl club of mantis shrimp [24], (b) SEM image of helicoidal fiber orientation [25], (c) SEM image of a single period [25], (d) schematic diagram of fiber orientation in a single period [25].

The fiber arrangement is shown schematically in Fig. 1(d). High impact resistance and absorbed energy are attributed to the dactyl club's quasi-isotropic helicoidal arrangement of mineralized fiber layers.

3. Materials and experimental methods

3.1 Materials

The aluminum used in this study was A1050 aluminum alloy sheets (0.3 mm thick) having a tensile strength of 107.37 MPa and proof stress of 85 Min MPa and the unidirectional S-glass fiber fabric of 220 g/m^2 for reinforcing into the matrix. The resin matrix was prepared by mixing 10 wt% of polyester epoxy resin with 1 wt% phenolic hardener as a curing agent supplied by Epoxy Resin Supplier Bangladesh. The aluminum alloy sheets were supplied by Iqbal Ahmed & Co., Dhaka and the unidirectional glass fiber fabric was by Fiber Region, Chennai, Tamil Nadu.

3.2 Surface treatment of Al sheets

To achieve better cohesive bonding between the aluminum sheets and the UGFRP, surface treatment of the aluminum sheets is necessary. Firstly, aluminum sheets were rubbed with emery paper and cleaned with acetone. Then, the sheets were immersed in 25g/L sodium hydroxide (NaOH) solution for 2 min and rinsed with tap water. After that, the sheets were immersed in 5% (vol.) HCl solution for 3 min and finally rinsed with distilled water. Both NaOH and HCl were supplied by Khulna Scientific Store, Khulna. Lastly, the sheets were dried at 37°C.

3.3 FML fabrication process

Inspired by the dactyl structure mentioned above, the core of the FML (UGFRP) was made using 10 layers of unidirectional glass fiber stacking one on the other by epoxy resin. Each ply of fiber was rotated 9 times by 20° completing a period of the helical structure of the dactyl club making UGFRP's angular orientation of [0°/20°/40°/60°/80°/100°/120°/140°/160°/180°]. The FML layup scheme was 2/9, 2 layers of surface treated aluminum sheets and 1 layer of UGFRP between them. The cohesive layer of epoxy was located between each of the aluminum sheets and the UGFRP surface.

A hand layup method was used to manufacture the FML and was kept at a curing pressure of 0.1 MPa to ensure good adhesion between the epoxy resin and the plies of fiber and aluminum sheets for 24h at 27°C. The FML production process is shown in Fig. 2. The overall thickness of the FMLs was 4.40 ± 0.03 mm.

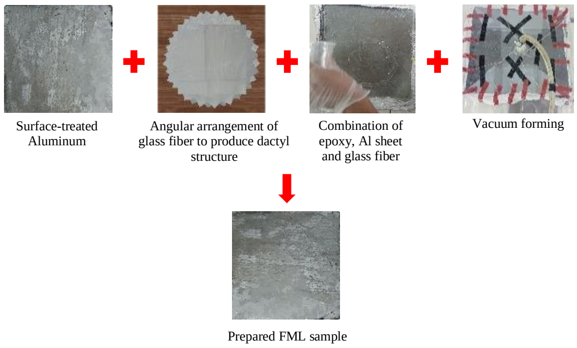


Fig. 2 FML fabrication process.

3.4 Mechanical tests

Various mechanical tests were conducted to characterize the fabricated FMLs. To guarantee the accuracy of the test findings, three specimens for the tensile properties and five specimens for the impact properties were examined in each test. The testing methods are discussed in the following sub-sections.

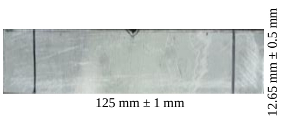
3.4.1 Tensile test

All FML specimens were tested for tensile properties as per ASTM D3039 [26] using Shimadzu AGXV (Japan) universal testing machine with a maximum loading capacity of 300kN. From the manufactured panel, rectangular specimens measuring 175 ± 1 mm × 25 ± 0.5 mm were cut out. The tensile test specimen is shown in Fig. 3.

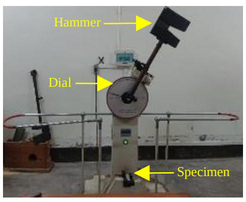
Fig. 3 Tensile test specimen with dimension.

3.4.2 Impact test

A Charpy impact testing machine was used to evaluate the impact resistance of the fabricated FMLs. The impact test was done following the ASTM D6110 standard [27]. The specimen used measured 125 mm ± 1 mm in length and 12.65 mm ± 0.5 mm in width, while the depth and notch angle were 3 mm ± 0.5 mm and 45° ± 0.5° respectively. The weight of the hammer was 20 kg. Fig. 4 (a) and (b) show the impact test specimen and the test setup.



(a)



(b)

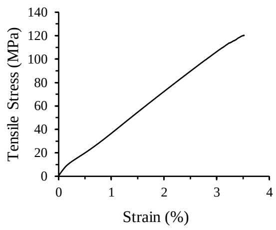
Fig. 4 Charpy impact test (a) specimen with dimension, (b) setup.

4. Results and discussion

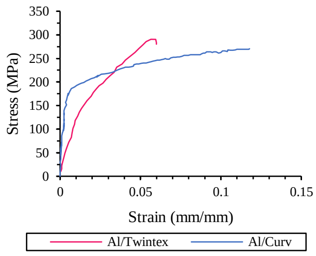
4.1 Tensile properties

5 samples were tested to determine the tensile strength of the UGFRP FMLs. Fig. 5 (a) shows the tensile stress-strain curves of the UGFRP FMLs. The figure shows that the FML exhibits a brittle behavior, involving significant plastic deformation up to the point of maximum load. The FML specimen failed catastrophically across the sample width at a maximum stress of 120.337 MPa having a maximum elongation of 6.166 mm. It is to be noted that, the Al/Curv samples were prepared by placing self-reinforced polypropylene (0.4 mm thick) between two aluminum sheets having a thickness of 0.3 mm each and Al/Twintex were fabricated by placing glass fiber-reinforced polypropylene between the same [4]. From Fig. 5 (b), the maximum stress of the Al/Twintex and Al/Curv is 290 MPa and 265 MPa, respectively. The Al/Curv samples showed a ductile behavior before plateauing the maximum stress whereas the Al/Twintex showed a brittle behavior as the reinforcement in the polypropylene matrix is itself a brittle material which enhances the brittleness of Al/Twintex.

Fig. 5 (c) compares the tensile strength and maximum elongation between the UGFRP FML, Al/Curv and Al/Twintex. The UGFRP FML holds 140.5 % and 119.92 % less tensile strength than that of the Al/Twintex and Al/Curv respectively which is attributed to high tensile strength retention of polypropylene (>90 %) than epoxy (70~80 %) [28]. In the case of maximum elongation, the UGFRP FMLs (6.17%) show 0.22% more and 5.61% less deformation than that of the Al/Twintex (5.94%) and Al/Curv (11.78%) respectively which is attributed to the brittle behavior of the UGFRP FML. The spiral geometry of the dactyl core helps resist the crack growth. The structure allows microcracks to realign their direction rather than spreading straight through the material, thus prolonging failure and allowing for larger deformations than Al/Twintex.



(a)



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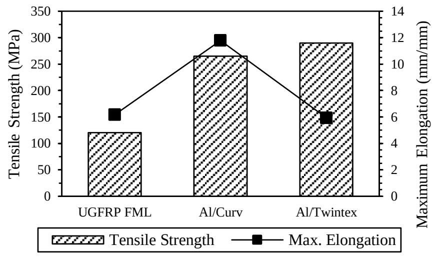

(c)

Fig. 5 Stress-strain diagram of (a) UGFRP FML, (b) Al/Curv and Al/Twintex [4], (c) tensile strength and maximum elongation of UGFRP, Al/Curv and Al/Twintex.

4.2 Impact properties

Fig. 6 shows the impact energy absorption of the UGFRP FMLs. 5 samples were tested to determine the impact energy absorption capability of the UGFRP FMLs. The figure illustrates that the UGFRP FML has a significant energy absorption property with an average energy absorption of 61.67 J. The GLARE-3 and GLARE-4 were manufactured by alternate layers of aluminum sheet and cross-ply arrangement glass fiber. The aluminum sheet thickness was 0.3 mm. GLAER-3 consists of 5 aluminum sheets with a nominal thickness of 2.54 mm and GLARE-4 consists of 3 aluminum sheets with a nominal thickness of 1.68 mm. GLARE-3 has an energy absorption value of 49 J whereas GLARE-4 has an energy absorption value of 26 J [23] which is 25.86% and 137.19% less than that of the UGFRP FML. Comparing these values, it is evident that the UGFRP FML has a moderate to high-impact resistance property. However, the overall thickness of aluminum in UGFRP FML is less than GLARE-3 and GLARE-4.

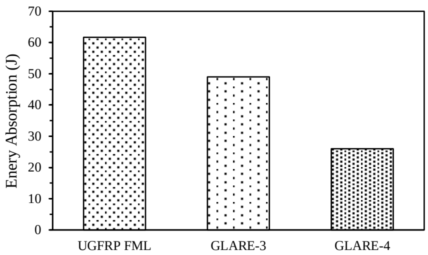

Fig. 6 Impact energy absorption.

The material is strengthened while allowing for deformation because of the compromise between stiffness and flexibility made possible by the dactyl structure. In applications where high-impact strength and toughness are needed, this helps the composite material elongate more under tension without losing its structural integrity.

5. Conclusion

In the paper, the tensile and impact-resistant properties of a UGFRP FML were compared with Al/Curv, Al/Twintex, GLARE-3 and GLARE-4 FMLs from the literature. The major outcomes from the study are-

- The tensile strength of UGFRP FML reduces significantly up to 140.5% and 119.92% compared to that of the Al/Curv and Al/Twintex composites. It also exhibits brittle behavior.
- The maximum elongation of UGFRP FML is between that of the Al/Curv and Al/Twintex composites which is attributed to the brittle behavior of the composite due to its helicoidal structure of the laminate core. This makes it suitable for engineering applications where high elongation to failure is needed.
- The energy absorption capability of the UGFRP FML is 25.86% and 137.19% more than that of the GLARE-3 and GLARE-4. This indicates that the UGFRP FMLs are particularly used for improving the structural properties of the aircraft fuselage and car body panel where high-impact resistance and energy absorption are mandatory.

Future studies on glass fiber-based dactyl-inspired fiber-metal laminates may concentrate on investigating other characteristics including thermal or electrical performance and fatigue behavior under cyclic loading. Mechanical performance may be improved by structural optimization using different stacking arrangements, fiber orientations, or weave patterns. Examining the addition of different matrix materials, alternative reinforcing fibers (such carbon or aramid), or hybrid designs could enhance material qualities even more. Long-term and environmental research, such as aging tests and durability in challenging environments like chemicals, humidity, or UV light, may shed light on performance over time. In addition to practical uses like crashworthiness in the automotive or aerospace sectors, numerical simulations like finite element modeling could be used to forecast behavior under various loading scenarios.

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