Al-Nahrain Journal for Engineering Sciences

Al-Nahrain J. Eng. Sci. 29(2) 247-259, 2026
Original Article

Mechanical Characterization of Multilayer Fiber-Reinforced Composite Materials

Amanj Ahmed Karim [1]•, Younis Khalid Khdir [2] •

1,2 Department of Mechanical and Energy Engineering, College of Technical Engineering, Erbil Polytechnic University, Erbil, Kurdistan Region, Iraq

•*These authors contributed equally to this work*

DOI: https://www.doi.org/10.29194/NJES.29020247

Received: Sep. 7, 2025 **Revised:** Oct. 10, 2025 **Accepted:** Dec. 15, 2025 **Published:** June 20, 2026

Abstract

The mechanical behavior of multilayer FRCMs was tested, and the effects of fibers, types of fiber, and laminates on the tensile, flexural, and impact properties were discussed. The vacuum bagging method is a composite manufacturing process that uses atmospheric pressure to consolidate laminate layers, remove excess resin, and get rid of air bubbles. This makes high-quality, void-free composites. Four composite systems were made using this method: natural fiber composites reinforced with sheep wool and goat hair fibers, and synthetic fiber composites reinforced with carbon and glass fibers, all with an epoxy resin (LR620) and hardener (LH620) system. All composite assemblies have been systematically characterized at different layer configurations (3-6 layers considered) for the best structural response. The tensile, flexural, and impact properties were tested by following the corresponding ASTM (D638, D790, D6110) standards, respectively. The tensile and flexural results of the carbon fiber composite (GCT, GCB series) showed excellent mechanical performance (maximum tensile strength of 283 MPa for GCT4 and flexural strength of 164 MPa for GCB5) with high load-carrying capacity, but the failure was brittle. Goat hair composites exhibited excellent impact resistance (GHI4: 1.255 J) and moderate tensile strength (36 MPa), which indicated superior energy absorption capacity. The glass fiber composites showed a good balance of mechanical properties with increased ductility, where the tensile strength was 245 MPa, and a large deflection capacity was reached (14.683 mm). The study demonstrates that 4-layer setups usually result in the highest tensile properties, while 5–6-layer setups improve the flexural strength. These results add to the knowledge of optimization of multilayer composite design, and they are very useful for materials selection in aerospace, automotive, and structural applications.

Keywords: *Multilayer composites, Fiber-reinforced composites, Vacuum bagging process, Epoxy matrix, Carbon fiber, Glass fiber, Sheep wool fiber, Goat hair fiber.*

Corresponding author: Provide the corresponding author information and publisher here. E-mail address: amanj.karim@epu.edu.iq

1. Introduction

Composite materials, such as fiber-reinforced composites (FRCs), nanocomposites, and fiber–metal laminates (FMLs), are increasingly used in the aerospace, automotive, marine, construction, and renewable energy industries because they have a better strength-to-weight ratio and better resistance to corrosion and temperature change, and they take up less space [1-3]. At first, "these materials" served as secondary members or coverings, but now they are integrated into the main load-carrying structures such as aircraft fuselages, wing panels, rotor blades, marine hulls, bridge decks, and wind turbine aerofoils [4-7].

Composite materials are made by combining two or more ingredients having different physical or chemical properties so that they complement each other and improve the overall behavior of the material [٨]. They consist mostly of resin (matrix) with fibers (for example) added to provide high axial strength and stiffness at low density. The matrix serves to maintain fiber orientation and transfers loads, plus protects economically against environmental damage [9]. Although the matrix is typically the least strong component, its primary function is to enhance toughness and damage tolerance by distributing stresses and preventing crack propagation.

Multilayer composites consist of multiple layers, primarily a sacrificial face sheet and a core. The sacrificial sheet absorbs the initial blast or impact energy to protect the core from damage. This is very important since cores are hard to fix and cost a lot of money [10]. Adding more layers may help make things more resistant to dynamic stresses by balancing stiffness, flexibility, and brittleness.

Mechanical qualities of items may be tailored to fulfill particular load needs. Multilayer structures offer enhanced energy absorption through sacrificial outer layers, improved maintenance by protecting core integrity, and optimized structural performance through tailored layer functionality. For example, the exterior layer should be stronger for energy absorption; thus, it may be produced from extremely strong materials, but when more ductility is necessary, and further down, it is a little bit less required. The high strength-to-weight ratio of multilayer composites makes them especially attractive for application in aerospace, automotive, and civil engineering, where structural strengthening and weight reduction are vital. Also, since the core is not exposed to harm, maintenance expenses are lowered and usable life extended. Finally, the option to repair just sacrificial layers that have degraded without harming the core itself enhances durability and economy [11].

The orientation of fibers in fiber-reinforced polymer (FRP) composite constructions is known to alter mechanical characteristics as well. Extensive research from several papers has been devoted specifically to this topic, which confirms that different fiber angles produce different results in tensile strength and stiffness. For example, 90° fiber orientation often gives high tensile strength in composites because the load distributes itself evenly among the fibers [12]. However, some studies showed as far back as twenty years ago that 0° fiber orientation gave the best values for strength and stiffness, as fibers were in line with the applied load [13, 14]. Others suggest that intermediate angles like 30° or 45° can lead to lower tensile strength due to uneven load transfer and differences in fracture mode [15, 16].

Unidirectional composites, with fibers mostly oriented in one direction, have been less studied. However, previously reported research yields uniform agreement that the maximum strength and stiffness are achieved by aligning fibers with the load direction [16, 17]. Tests show that as the fiber angle increases from 0° to 45°, strength and stiffness deteriorate rapidly. Microscopic analysis reveals that failure occurs mainly due to fiber breakage, rather than matrix cracking or fiber pull-out.

The orientation of the fibers has a big effect on the tensile qualities. For example, a 0° orientation gives the best mechanical performance because it aligns the load along the fiber path, which reduces stress concentrations.

This study seeks to fill the research void in the comparative mechanical characterization of natural and synthetic multilayer composites, focusing on the influence of fiber type, layer count, and stacking sequence on tensile, flexural, and impact properties for enhanced composite design.

1.1. Composite Manufacturing Process

There are two different methods of producing composite materials: open and closed molding. With the former, the dyed resin and fiber are exposed to moisture and may have a difficult-to-control surface finish. The commonest open manufacture methods are the hand layup type, the spraying layup method, and the filament winding process. In hand layup, one lays resin-impregnated fiber layers (unidirectional or woven cloth) in a mold and then compresses them with rollers. Fiber–resin ratios (e.g., 40:60, 50:50, 60:40) influence properties—higher fiber content increases brittleness, while a 50:50 ratio is good for toughness. This form is cheap and flexible, but slow and very labor-intensive [18-22].

The spray layup process uses the chopped fibers and resin that are sprayed into a mold, for light-weight products like bathtubs, glass, or natural fibers reinforced plastics. It has the advantages of implementing amendments during fabrication and correction of a finished article, but lacks quality stability for the cost suffered by the presently endured long product cycle [23-26].

Filament winding is fibers wrapped about a rotating mandrel and is suitable for making pipes, tanks, and aerospace components. Mechanical qualities depend on the wrap angle; nevertheless, production is more costly and needs mandrels to be customized precisely when removing them from pieces that have been made [27-30].

Closed molding or liquid composite molding (LCM) is more suited to manage resin flow than open ones. Techniques include vacuum infusion, pultrusion, resin transfer molding (RTM), vacuum bagging, and light RTM (LRTM).

Vacuum infusion employs vacuum pressure to draw resin into the fiber preform, with less auxiliary material and cheaper cost in exchange for complexity in application across large constructions [31-33]. The newest thermoplastic polymers, such as APA-6, now allow for larger integrated, bigger portions [34, 35].

Pultrusion pulls continuous fibers out of a heated die; this offers us great strength and uniform sections at low cost--but the price of tooling up holds back progress [36-38].

Vacuum bagging uses atmospheric pressure via a vacuum bag, displacing gas from between layers to improve fiber content and eliminate voids. However, this adds to the expense and necessitates a high degree of expertise [39-41].

Resin Transfer Molding (RTM) injects resin into the mold to create strong composites with low voids, suitable for small parts, but is limited both by tooling costs and size [42, 43].

A hybrid method, Light Resin Transfer Molding (LRTM), a hybrid technology of vacuum bagging and compression molding, offers shorter curing times and better control of resins. It produces strong structural as well as electronic parts, but is expensive in terms of tooling and handling [44, 45].

2. Experimental Study

2.1. Materials

The study looks at what happens to the mechanical properties of composites when several kinds of reinforcements and epoxy as a matrix are used. Natural fibers (such as sheep wool and goat hair), synthetic fibers (such as carbon and glass). All of them have been subjected to experimental examination in this paper.

The characteristics of each material used are explained below.

2.1.1. Epoxy

A blend of the LR620 epoxy resin system and LH620 hardener was used to prepare samples. This blend served to fix and act as an adhesive, made up at the correct mixing rate. Before mixing each method, the temperature of the material was kept between 15°C and 25°C. In such a system, Part A is the base resin, while Part B is the curing agent (reactor A). The specified mixing ratio is by weight: 100:20. The two components were well mixed for about 3–5 minutes until uniform.

2.1.2. Plain Woven Carbon Fabric

The 200g bidirectional plain weave carbon fabric is a type of carbon fiber known for its unique web-like weave pattern. It is also sometimes called FRP fiber. In this type of weave, the carbon fibers are interwoven in warp and weft at a 90-degree angle. This type of weave gives the 200g plain weave bidirectional carbon fabric properties such as strength, stability, and a smooth surface in parts, as shown in Figure 1.

2.1.3. Plain Woven Glass Fabric

Fiber glass Plain Weave Cloth 200g, E-glass fiber is made into woven glass fiber fabric, while the "Plain Weave" method is employed. It is a composite material made of molten glass. The fibers are very thin, long strands of material and are produced in the form of fabric or tape. Glass fiber has high tensile and flexural strength, and it also resists corrosion and abrasion, as shown in Figure 1.

(a) (b)

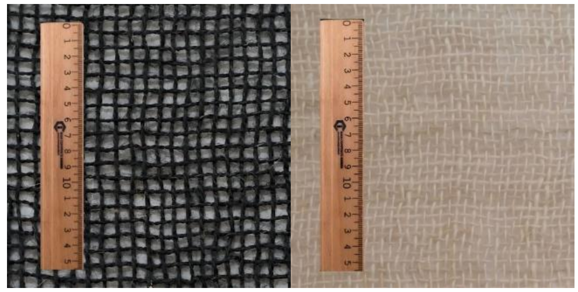
Figure 1. (a) Plain woven carbon fabric, (b) Plain woven glass fabric

2.1.4. Sheep Wool Plain Fabric

Sheep wool fiber is a natural fiber obtained from the fleece of sheep. It is mainly composed of a protein called keratin and is known for its natural elasticity and distinctive crimp. Sheep wool fiber is a special kind of natural animal fiber that comes in long and fine strands. It is spun to make yarns, usually felted for the construction fibers or insulation mats. These fibers have excellent sound absorption and thermal insulating properties, as well as being able to absorb or release moisture, making them suitable for many different purposes, as shown in Figure 2.

2.1.5 Goat Hair Plain Fabric

Goat hair fiber is a natural fiber obtained from the fleece of goats. This product is principally made of keratin, a protein-based fiber, and it is esteemed for its fine feel, natural crimping, lightness, and warmth-insulating properties. Depending on the breed, goat hair fibers may be very fine and silky (as in cashmere or mohair) or coarser (as in ordinary goat guard hair). These fibers are often spun up into top-quality yarns or felted to produce fabrics, mats for insulation against cold weather, or specialty cloths. It provides excellent heat insulation, maintains a moderate humidity, and feels so luxuriously soft and clingy. Goat hair fibers can be put to work in a wide variety of areas, as shown in Figure 2.



(a) (b)

Figure 2. (a) Sheep wool plain fabric, (b) goat hair plain fabric

2.2. Fabrication of Multilayer Composite

Vacuum bagging is a widely used process for producing high-quality laminated composite parts. In this method, the layers of fiber reinforcement (such as carbon, glass, or natural fibers) are manually placed in a mold and impregnated with resin (either by hand lay-up or using pre-impregnated (prepreg) materials). Once the lay-up is complete, the entire assembly is covered with a flexible vacuum bag, which is sealed tightly around the edges of the mold, as shown in Figure 3.

A vacuum pump removes the air from inside the bag, applying uniform atmospheric pressure to the lay-up. This pressure consolidates the laminate, removes excess resin and air bubbles, and improves the fiber-to-resin ratio. The result is a stronger, lighter, and void-free composite part, as shown in Figure 4

Vacuum bagging is commonly used in the aerospace, marine, automotive, and sports industries for medium-to high-performance parts that require a good surface finish and mechanical properties.

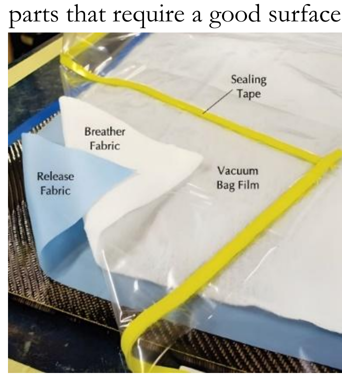


Figure 3. Vacuum bagging

.

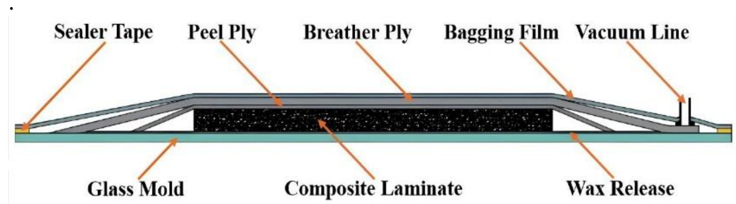


Figure 4. Vacuum bagging diagram

2.2.1. Multilayer Composite Vacuum Bagging Process

The vacuum bagging process is widely used to manufacture high-quality, fiber-reinforced parts with controlled thickness and fiber volume fraction and minimal void content, especially in multilayer composite laminates with dimensions 225 mm × 250 mm.

- Mold Preparation:

The mold surface is cleaned and coated with a suitable release agent to prevent the laminate from sticking. A mold release film may also be used, as shown in Figure 5.

Figure 5. Glass mold preparation showing application of sealant tape and mold release wax

- Lay-Up:

Multiple layers (plies) with dimensions 225 mm × 250 mm of dry fabric or prepreg (pre-impregnated with resin) are stacked on the mold according to the desired fiber orientation sequence (e.g., [45°/0°/-45°]). Each ply is carefully placed to ensure proper alignment and avoid wrinkles or bridging, as shown in Figure 6.

(a) (b)

Figure 6. Layer stacking sequence (a) Before resin impregnation, (b) After resin impregnation

- Insertion of Peel Ply and Breather:

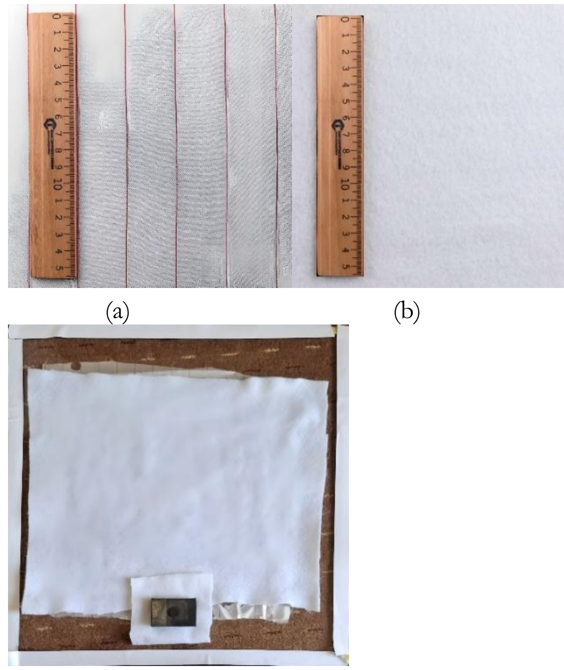
A peel ply is placed over the laminate to provide a textured surface for secondary bonding or painting. A perforated release film and a breather/bleeder fabric are added on top to allow air and excess resin to escape during vacuum application, as shown in Figure 7.

- Bagging:

A flexible vacuum bagging film is placed over the entire lay-up, with the edges sealed to the mold flange using tacky tape or sealant tape so that an airtight enclosure results, as shown in Figure 8.

- Vacuum Application:

A vacuum pump is connected to the bag using a vacuum port. In this way, air will be evacuated if possible, compressing the laminate under atmospheric pressure (typically -0.8 to -1 bar). The vacuum removes trapped air and any volatile gases, causing poor compaction, increasing resin flow rate as well as fiber wet-out percentage, as shown in Figure 9.



(a) (b)

Figure 7. Multiple layers (plies) with (a) Peel ply, (b) Breather ply

Figure 8. Multiple layers (plies) with bagging film

Figure 9. Multiple layers (plies) after vacuum Bagging

- Curing:

For wet lay-up, the part may be left under vacuum at room temperature or taken to an oven with accelerated curing. For prepregs, curing with heat often requires elevated temperatures, and in carbon fiber applications, occasionally it is necessary to apply additional pressure, which can only be provided by an autoclave.

- Demolding and Finishing:

After full curing, the vacuum bag, breather, and peel ply are removed. The cured laminate is demolded, trimmed, and finished as required. These steps are repeated for each composite sample to verify its mechanical properties, as shown in Figure 10 and Table 1.

Figure 10. Multilayer (a) sheep wool, (b) goat hair, (c) carbon, (d) glass) fiber composite laminates

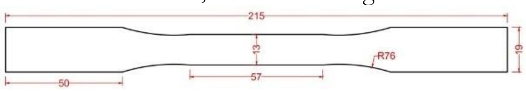
Table 1. Properties of multilayer (sheep wool, goat hair, carbon, glass) fiber composite laminates

Fiber Material	Matrix Epoxy	Number of Layers	Layer Orientations (deg)	Total Weight (g)	Fiber (%)	Matrix (%)	Fiber Thickness (mm)	Sheet Thickness (mm)	Woven Distance (mm)
Sheep	LR 620	3	45,0,-45	225.25	30.17	69.83	2	4.25	5
Wool		4	45,0,90,-45	287.35	30.12	69.88	2	4.55	5
Fiber		5	0,45,90,-45,0	330.55	30.12	69.88	2	5.55	5

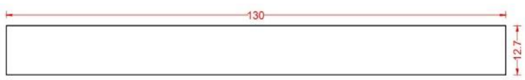
		6	0,45,90,90,-45,0	370.45	30.17	69.83	2	5.25	5
Goat Hair Fiber	LR 620	3	45,0,-45	507.63	30.15	69.85	6	7.6	10
		4	45,0,90,-45	655.06	30.16	69.84	6	9.8	10
		5	0,45,90,-45,0	716.23	30.15	69.85	6	11.2	10
		6	0,45,90,90,-45,0	796.98	30.16	69.84	6	12.4	10
Carbon Fiber	LR 620	3	45,0,-45	52.02	69.42	30.58	0.25	0.75	2
		4	45,0,90,-45	65.55	69.18	30.82	0.25	1	2
		5	0,45,90,-45,0	81.61	69.28	30.72	0.25	1.25	2
		6	0,45,90,90,-45,0	98.77	69.12	30.88	0.25	1.5	2
Glass Fiber	LR 620	3	45,0,-45	47.63	76.67	23.33	0.2	0.6	1.5
		4	45,0,90,-45	63.4	76.36	23.64	0.2	0.8	1.5
		5	0,45,90,-45,0	80.58	76.40	23.60	0.2	1	1.5
		6	0,45,90,90,-45,0	92.92	76.70	23.30	0.2	1.2	1.5

2.2.2. Fabrication of The Specimens

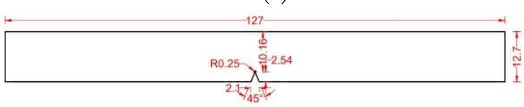
For each test, the sample design with a standard ASTM was created using AutoCAD 2024, with specific parameters tailored to the requirements of each test, as shown in Figure 11. The prepared composite samples were then cut to the designed dimensions using a CNC laser machine, as shown in Figure 12.



(a)



(b)



(c)

Figure 11. AutoCAD drawing (a) Tensile test specimen, (b) Flexural test specimen, (c) Impact test specimen

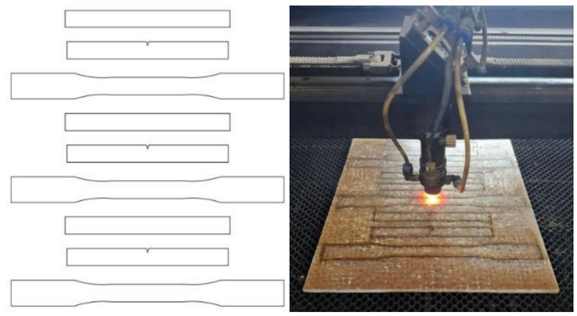


Figure 12. AutoCAD drawing and CNC laser machine

3. Mechanical tests

To carry out the mechanical tests, that is, tensile, flexural, and impact, samples were grouped to form a system; each sample was also assigned its orientation code. In this study, four kinds of primary synthetic-fiber-reinforced composites have been made: one was natural sheep wool, and another was goat hair fiber mixed with resins; the remaining two were artificial glass and carbon fibers reinforced with resins. Each primary composite laminate group was subdivided into 4 subgroups based on the number of laminate layers needed. Three, four, five, and six were the choices, respectively, for any group. Samples are arranged in order, and the number of samples in each group is shown in Table 2.

Table 2. Specimen coding for experimental testing

Composite Material	Number of Layers	Tensile Groups			Flexural Groups			Impact Groups		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Sheep Wool Fiber	3	GWT31	GWT32	GWT33	GWB31	GWB32	GWB33	GWI31	GWI32	GWI33
	4	GWT41	GWT42	GWT43	GWB41	GWB42	GWB43	GWI41	GWI42	GWI43
	5	GWT51	GWT52	GWT53	GWB51	GWB52	GWB53	GWI51	GWI52	GWI53
	6	GWT61	GWT62	GWT63	GWB61	GWB62	GWB63	GWI61	GWI62	GWI63
Goat Hair Fiber	3	GHT31	GHT32	GHT33	GHB31	GHB32	GHB33	GHI31	GHI32	GHI33
	4	GHT41	GHT42	GHT43	GHB41	GHB42	GHB43	GHI41	GHI42	GHI43
	5	GHT51	GHT52	GHT53	GHB51	GHB52	GHB53	GHI51	GHI52	GHI53
	6	GHT61	GHT62	GHT63	GHB61	GHB62	GHB63	GHI61	GHI62	GHI63
Carbon Fiber	3	GCT31	GCT32	GCT33	GCB31	GCB32	GCB33	GCI31	GCI32	GCI33
	4	GCT41	GCT42	GCT43	GCB41	GCB42	GCB43	GCI41	GCI42	GCI43

	5	GCT51	GCT52	GCT53	GCB51	GCB52	GCB53	GCI51	GCI52	GCI53
	6	GCT61	GCT62	GCT63	GCB61	GCB62	GCB63	GCI61	GCI62	GCI63
Glass Fiber	3	GGT31	GGT32	GGT33	GGB31	GGB32	GGB33	GGI31	GGI32	GGI33
	4	GGT41	GGT42	GGT43	GGB41	GGB42	GGB43	GGI41	GGI42	GGI43
	5	GGT51	GGT52	GGT53	GGB51	GGB52	GGB53	GGI51	GGI52	GGI53
	6	GGT61	GGT62	GGT63	GGB61	GGB62	GGB63	GGI61	GGI62	GGI63

3.1. Tensile Test

This test was performed according to ASTM D638 type I specimens standard were used for tensile testing. The XHG-50 Ring Stiffness Tester, equipped with a sample slicer and software displaying all test parameters, was used. The crosshead speed was set to 5 mm/min, and the machine operated with a 100 kN load cell under advanced control. The tensile specimens are shown in Figure 13.

Figure 13. Tensile test specimens (sample 2)

3.2. Flexural Test

This test was performed according to ASTM D790 using the GT-AI-3000 testing machine. A crosshead rate of 10 mm/min was applied for the composite specimens with a span length of 80 mm. Load and deflection data were recorded using a smart screen recorder. The specimens for the flexural tests are shown in Figure 14.

Figure 14. Flexural test specimens (sample 2)

3.3 Impact Test

This test was performed according to ASTM D6110. The XJJD-50 series Charpy impact testing machine, designed for testing metals and plastics, was used. Load and energy absorption details were recorded using a smart screen recorder. The impact test specimens are shown in Figure 15.

Figure 15. Impact test specimens (sample 2)

4. Results and Discussion

4.1. Tensile Test

Based on Figure 16 and the complete data provided in both Table 3 and Figure 17, there are a few key observations about the mechanical behavior of these fiber-reinforced composite substances. The (GCT series) of carbon fiber composites has better mechanical characteristics. GCT4 has the greatest breaking stress of 283 MPa, while GCT3 has the second highest at 199 MPa. This shows that carbon fiber reinforcement is far more robust to stresses than any other kind of fiber reinforcement. The goat hair fiber composites (GHT series) don't work very well mechanically. Their stress range is already limited, between 25 and 36 MPa. GHT3 performs best at 36 MPa, indicating that natural goat hair fibers are capable of giving moderate reinforcement while achieving a relatively high elongation. After stress level values, the wool fiber composite test (GWT series) and the glass fiber composite test (GGT series) both come out last in performance of all mechanical tests carried out throughout this trial. GGT series limit strain value (5.04-6.51%) surpasses its designed upper limit, but still shows better performance than when GWT systems not only fall short of the goal but also have lower failure strain and a non-linear relationship in the stress-strain state in the opposite direction to the original design intention. This manifests in all four distinct behavior formats below stress parameters given above: carbon fiber composites feature sudden failure after a steep rise–a typical presentation of brittle behavior; goat hair composite plasticity while retaining moderate elasticity; wool-like glass fiber composite materials extend their post-yield area visually indicating more ductile failure modes. Carbon fiber composites display brittle failure owing to their high stiffness and limited elongation capacity, whereas goat hair composites show plasticity and mild elasticity coming from their natural fiber structure and better strain tolerance. The stacking strategy (layers 3-6) may also have a big impact on performance. Four layers usually provide the best performance for most kinds of fibers, but not always. This means that the optimum outcomes for all fiber types may be achieved by finding the right balance between the volume percentage of fibers and the interactions between fibers and the matrix. Four layers generally give the best tensile performance owing to balanced stress distribution and reduced interfacial defects, with fiber volume fraction and fiber-matrix adhesion crucially determining strength optimization.

Figure 16. Tensile test specimens (sample 2)

An effort was made to create better terms for composite material evaluation. Also, these findings emphasize the trade-off between strength and affinity in composite materials. Carbon fibers are quite strong but don't stretch much. Natural fibers like goat hair or wool are somewhat strong and become softer with time—the way the fibers are arranged and the kind of fiber affect how the complete material behaves. The difference in the number of laminate layers (3–6) has a big effect on how well the material works mechanically since it alters the fiber volume fraction and stress distribution. Four layers generally give excellent tensile qualities by balancing fiber-matrix interactions, whereas 5–6 layers boost flexural strength via increased moment of inertia according to thick-beam theory.

Table 3. Tensile test results

Composite Samples	Load (N)	Stress (MPa)	Strain (%)
GWT3	319	6	0.80
GWT4	732	13	1.12
GWT5	1202	18	1.98
GWT6	1204	19	2.21
GHT3	3369	36	3.10
GHT4	3036	25	2.49
GHT5	4538	33	3.83
GHT6	4169	28	3.58
GCT3	1821	199	3.78
GCT4	3456	283	3.64
GCT5	2746	180	3.14
GCT6	1244	68	2.93
GGT3	1038	142	5.06
GGT4	2036	209	5.84
GGT5	2988	245	6.26
GGT6	3510	240	6.51

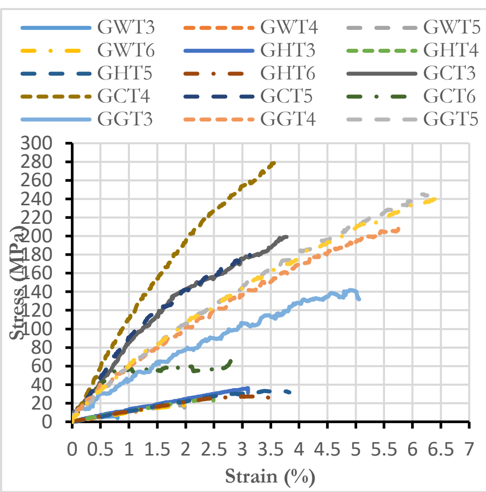


Figure 17. Tensile test stress-strain curves

4.2. Flexural Test

Based on Figure 18 with the comprehensive analysis of flexural experiments described in Table 4 and Figure 19, several of the most significant effects on both flexural behavior as well as mechanical performance for a fiber-directed resin composite subjected to three-point bending conditions can be summed up as follows, depending upon the circumstances. The carbon fiber composites (GCB series) are particularly good at flexing -- so GCB5 achieves a maximum flexural stress of 164 MPa and GCB6 134 MPa, which shows strength in their resistance to bending moments and their structural rigidity though they exhibit maybe a bit low deflection (8.303-17.613 mm), is more of a brittle failure. Glass fiber composites (GGB series) also have a moderate strength of flexural performance with GGB6's 134 MPa, while much higher (11.310-14.683 mm) fold compared to carbon fiber composites roll back somewhat confusingly since this statement implies that carbon fiber composite bending behavior is far and of a greater degree than what one would hope for. The natural fiber composites have different flexural behaviors: wool fiber composites (GWB series) have just moderate flexural stress values, ranging between 39-52 MPa and deflection is also on the low side (3.663- 4.497 mm); on the other hand, goat hair fiber composites (GHB series) show stress levels that are close to wool but their deflection values do not exceed fast breaking for brittle behavior. Carbon fiber composites display significant flexural stress but minimal deflection owing to their intrinsic brittleness, whereas natural fiber composites retain ductility via fiber flexibility and energy dissipation processes.

Figure 18. Flexural test specimens (sample 2)

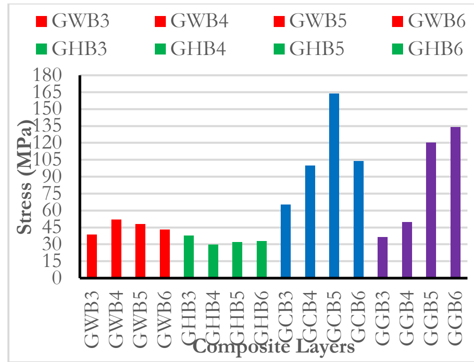
Flexural performance is highly impacted by the kind and number of layers, with the highest such effect occurring at 5-6 layers. In general, adopting this layer structure delivers high flexural strength for carbon fibers as well as glass ones. Thick-sliced- beam theories corroborate Shaw's observations that thick laminates are more resistant to breaking because they have larger moments of inertia, which can take bending stress more readily than a thinner one can. Increasing laminate thickness boosts flexural strength according to thick-beam theory ($I \propto t^3$), with layer organization improving bending resistance via improved neutral axis location and stress distribution. This strain study demonstrates that carbon fiber composites yield higher values on the stress-to-strain ratios and are consequently more suited for flexural modulus. Natural fiber composites, however, do not present as big an instance owing to their lower modulus numbers, but still demonstrate appropriate ductility, which illustrates diametrically opposing aspects concerning flexure strength and flexibility.

Table 4. Flexural test results

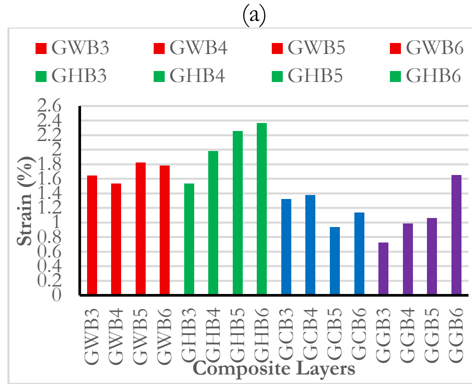
Composite Samples	Load (N)	Displacement (mm)	Stress (MPa)	Strain (%)
GWB3	59.8	4.497	39	1.644
GWB4	84.4	4.100	52	1.538
GWB5	137.5	3.663	48	1.820
GWB6	109.8	3.797	43	1.780
GHB3	216.1	2.187	38	1.538
GHB4	290.2	2.153	30	1.978
GHB5	395.7	2.190	32	2.258
GHB6	487.1	2.083	33	2.363
GCB3	4.2	17.613	65	1.321
GCB4	10.2	14.687	100	1.377
GCB5	24.0	8.303	164	0.934
GCB6	23.7	8.097	104	1.139
GGB3	1.4	12.417	37	0.722
GGB4	3.2	13.163	50	0.987
GGB5	12.2	11.310	120	1.060
GGB6	19.6	14.683	134	1.652

4.3. Impact Test

Based on Figure 20, let's take a look at the results of the impact test, Table 5, and Figure 21, which also offered us findings of considerable relevance on the impact resistance properties of these fiber-reinforced composite materials under dynamic load. Across all layer configurations, goat hair fiber composites (GHI series) were found to have greater impact resistance than sheep wool (GWI series), carbon (GCI series), and glass (GGI series) fiber composites. The greatest energy values of goat hair-based fiber (GHI) composites range from 0.945 J (GHI3) to 1.297 J (GHI6), with matching toughness values ranging from 105-128 J/m. Goat hair composites have superior impact resistance owing to their natural crimped structure and energy-absorbing capabilities via fiber pull-out and deformation processes, despite their lower tensile strength compared to brittle carbon fibers. This implies that the intrinsic fibrous structure of a goat's hair, to a significant degree, permits it to transmit impact while maintaining extreme resistance, even when a raw material or fake solid is shattered flat. The glass fibers (GGI series), on the other hand, only attained 0.328-1.032 J impact energies - an intermediate result between all attributes. The layer effect experiment reveals that increasing fiber layers here from 3 to 6 typically enhances impact resistance for all the materials. However, in 4-5 layers, these goat hair composites produce the greatest performance (GHI4: 1.255 J, GHI5: 1.234 J) and then decline progressively after 6 layers, when there's approximately twice the thickness for a given surface stress. The explanation behind this phenomenon might be either local stress concentration or interface failure owing to layer separation and peeling away under an abrupt load impact.



(a)



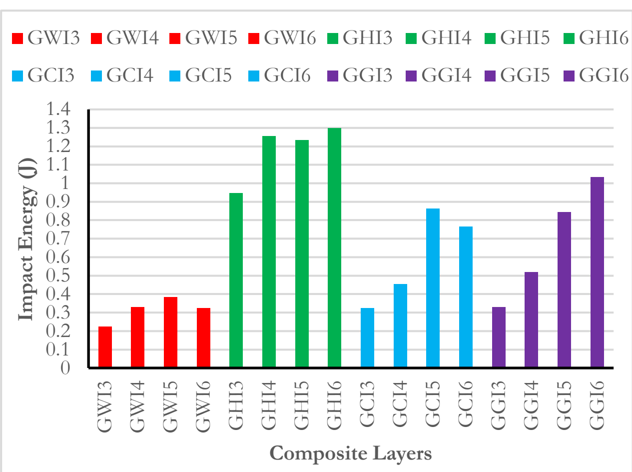
(b)

Figure 19. Composite materials (a) Flexural stress, (b) Flexural strain

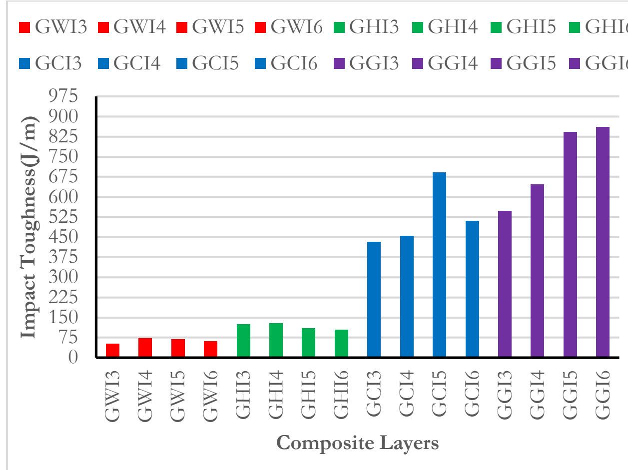
Figure 20. Impact test specimens (sample 2)

Table 5. Impact test results

Composite Samples	Impact Energy (Joule)	Impact Toughness (J/m)
GWI3	0.224	53
GWI4	0.329	72
GWI5	0.383	69
GWI6	0.323	62
GHI3	0.945	124
GHI4	1.255	128
GHI5	1.234	110
GHI6	1.297	105
GCI3	0.324	432
GCI4	0.454	454
GCI5	0.863	690
GCI6	0.765	510
GGI3	0.328	547
GGI4	0.517	647
GGI5	0.843	843
GGI6	1.032	860



(a)



(b)

Figure 21. Composite materials (a) Impact energy, (b) Impact toughness

5. Conclusion

This work fully studied the mechanical performance of multilayer fiber-reinforced composites utilizing both natural (sheep wool, goat hair) and synthetic (carbon, glass) fibers with 3–6 layer configurations. The important results are:

1. Mechanical Performance Comparison:

- Carbon fiber composites had better tensile strength (283 MPa for GCT4) and flexural strength (164 MPa for GCB5), but exhibited brittle failure behavior with limited deflection capacity (8.303-17.613 mm).
- Goat hair composites demonstrated outstanding impact resistance (1.255 J for GHI4) and energy absorption (128 J/m), despite modest tensile strength (36 MPa for GHT3).
- Glass fiber composites exhibited balanced mechanical qualities with strong tensile strength (245 MPa for GGT5) and high ductility (14.683 mm deflection).
- Sheep wool composites demonstrated mediocre mechanical characteristics but provide environmental benefits.

2. Layer Optimization:

- 4-layer arrangements consistently delivered maximum tensile performance across all fiber types, establishing the greatest compromise between fiber volume fraction and stress distribution.
- 5–6 layer layouts considerably increased flexural strength, with thickness increasing following thick-beam theory ($I \propto t^3$) principles.
- The ideal layer count varies with loading type: 4 layers for tension-dominated applications, 5-6 layers for bending-dominated applications.

3. Fiber-Matrix Interactions:

- Natural fibers exhibited higher energy absorption via fiber pull-out and deformation processes.

- Synthetic fibers gave better stiffness and strength, but with brittle failure characteristics.
- Fiber orientation (0°) considerably altered mechanical properties, with the best load alignment along fiber direction.

4. **Practical Implications:**
   - Carbon fiber composites are suggested for high-strength applications in the aerospace and automotive industries.
   - Natural fiber composites provide sustainable solutions for impact-resistant applications with environmental benefits.
   - Layer optimization may greatly boost certain mechanical qualities depending on application requirements.
5. **Future Research Directions:**
   - Hybrid natural-synthetic fiber blends for enhanced performance.
   - Surface treatment of natural fibers to increase fiber-matrix adhesion.
   - Long-term durability tests under varied environmental conditions.

6. References

[1] R. Yang and Y. He, "Optically and non optically excited thermography for composites: A review," Infrared Phys. Technol., vol. 75, pp. 26-50, 2016. https://doi.org/10.1016/j.infrared.2015.12.026

[2] M. E. Ibrahim, "Nondestructive evaluation of thick section composites and sandwich structures: A review," Compos. Part A Appl. Sci. Manuf., vol. 64, pp. 36-48, 2014. https://doi.org/10.1016/j.compositesa.2014.04.010

[3] C. Garnier, M. L. Pastor, F. Eyma, and B. Lorrain, "Detection of aeronautical defects in situ on composite structures using nondestructive testing," Compos. Struct., vol. 93, no. 5, pp. 1328-1336, 2011. https://doi.org/10.1016/j.compstruct.2010.10.017

[4] H. Tuwair, J. Drury, and J. Volz, "Testing and evaluation of full scale fiber reinforced polymer bridge deck panels incorporating a polyurethane foam core," Eng. Struct., vol. 184, pp. 205-216, 2019. https://doi.org/10.1016/j.engstruct.2019.01.104

[5] A. Parghi and M. S. Alam, "Application of sprayed FRP composites for strengthening concrete and masonry structures: A review," Compos. Struct., vol. 187, pp. 518-534, 2018. https://doi.org/10.1016/j.compstruct.2017.11.085

[6] P. J. Schubel, R. J. Crossley, E. K. G. Boateng, and J. R. Hutchinson, "Structural health and cure monitoring techniques for large wind turbine blades: A review," Renew. Energy, vol. 51, pp. 113-123, 2013. https://doi.org/10.1016/j.renene.2012.08.072

[7] M. E. Ibrahim, "Nondestructive testing and structural health monitoring of marine composite structures," in Marine Applications of Advanced Fibre Reinforced Composites, J. Graham Jones and J. Summerscales, Eds. Cambridge, UK: Woodhead Publ., 2016, pp. 147-183. https://doi.org/10.1016/B978-1-78242-250-1.00007-7

[8] R. B. Heslehurst, Defects and Damage in Composite Materials and Structures. Boca Raton, FL: CRC Press, 2014. https://doi.org/10.1201/b16765

[9] C. Meola, S. Boccardi, and G. Carlomagno, Infrared Thermography in the Evaluation of Aerospace Composite Materials. 2016. https://doi.org/10.1016/B978-1-78242-171-9.00003-6

[10] P. R. Hampson and M. Motamedi, "Composite structures subjected to dynamic loading: A review," Int. J. Crashworthiness, vol. 12, no. 4, pp. 411-428, 2014. https://doi.org/10.1080/13588260701483334

[11] S. Ali, X. Liu, S. Fawzia, J. Wu, and Y. Gu, "Behavior of multilayer composite structures under dynamic loading: A review," Int. J. Struct. Civ. Eng. Res., vol. 5, no. 1, pp. 44-51, 2016.

[12] P. Banakar, "Preparation and characterization of carbon fiber reinforced epoxy composites," IOSR J. Mech. Civ. Eng., vol. 1, pp. 15-18, 2012. https://doi.org/10.9790/1684-0131518

[13] M. Bourchak and W. Harasani, "Analytical and experimental investigation of tensile properties of cross ply and angle ply GFRP laminates," Sci. Eng. Compos. Mater., vol. 0, pp. 1-5, 2013.

[14] B. O. Samuel, D. S. Yawas, and I. O. Akpan, "Effect of fiber content and orientation on tensile strength of GFRP epoxy composites for pipe production," Res. Square, 2022.

[15] H. V. Patel and H. K. Dave, "Effect of fiber orientation on tensile strength of thin composites," Mater. Today Proc., vol. 46, pp. 8634-8638, 2021. https://doi.org/10.1016/j.matpr.2021.03.598

[16] H. Rahmani, S. H. M. Najafi, S. Saffarzadeh Matin, and A. Ashori, "Mechanical properties of carbon fiber/epoxy composites: Effects of plies, fiber content, and angle ply layers," Polym. Eng. Sci., vol. 54, no. 11, pp. 2676-2682, 2014. https://doi.org/10.1002/pen.23820

[17] A. Parmiggiani, M. Prato, and M. Pizzorni, "Effect of fiber orientation on tensile and flexural behavior of continuous carbon fiber composites made via fused filament fabrication," Int. J. Adv. Manuf. Technol., vol. 114, no. 7, pp. 2085-2101, 2021. https://doi.org/10.1007/s00170-021-06997-5

[18] M. Elkington, L. D. Bloom, C. Ward, and A. Chatzimichali, "Hand layup: Understanding the manual process," Adv. Manuf. Polym. Compos. Sci., vol. 1, p. 2055035915Y.000, 2015. https://doi.org/10.1179/2055035915Y.0000000003

[19] A. Swapnil, B. Sathe Sandip, P. Chaudhari Bapu, and V. Jagadale, "Mechanical properties of glass fiber/epoxy composites with variable volume fraction," Mater. Today Proc., vol. 4, pp. 9487-9490, 2017. https://doi.org/10.1016/j.matpr.2017.06.209

[20] A. P. D. M. S. El Wazery, M. I. El Elamy, and S. Zoalfakar, "Mechanical properties of glass fiber reinforced polyester composites," Int. J. Appl. Sci. Eng., vol. 14, pp. 121-131, 2017.

[21] R. Sakthivel and D. Rajendran, "Mechanical properties of hybrid polymer composite plates: Experimental investigation," Int. J.

Eng. Trends Technol., vol. 9, pp. 407-414, 2014. https://doi.org/10.14445/22315381/IJETT-V9P278
[22] G. S. Mutalikdesai, C. J. Raju, J. Moses, and V. Jose, "Mechanical characterization of epoxy/basalt/flax hybrid composites," Am. J. Mater. Sci., vol. 7, no. 4, pp. 91-94, 2017.
[23] B. Xiao, Y. Yang, X. Wu, M. Liao, R. Nishida, and H. Hamada, "Hybrid laminated composites molded by spray lay up," Fibers Polym., vol. 16, no. 8, pp. 1759-1765, 2015. https://doi.org/10.1007/s12221-015-5298-6
[24] S. K. Ha, J. G. Jang, S. H. Park, and H. K. Lee, "Advanced spray multiple layup process for quality control of sprayed FRP composites," J. Constr. Eng. Manag., vol. 141, 2014. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000905
[25] S. K. Ha, S. Na, Y. G. Bang, and H. K. Lee, "Sag resistance and applicability of sprayed FRP systems on vertical and overhead concrete surfaces," Mater. Struct., vol. 48, 2013. https://doi.org/10.1617/s11527-013-0165-7
[26] T. Kikuchi, Y. Tani, Y. Takai, A. Goto, and H. Hamada, "Mechanical properties of jute composites by spray up fabrication," Energy Procedia, vol. 56, pp. 289-297, 2014. https://doi.org/10.1016/j.egypro.2014.07.160
[27] L. Zu, H. Xu, B. Zhang, D. Li, B. Zi, and B. Zhang, "Design and production of filament wound composite square tubes," Compos. Struct., vol. 191, 2018. https://doi.org/10.1016/j.compstruct.2018.02.069
[28] J. Fleischer and J. Schaedel, "Joining automotive space frame structures by filament winding," CIRP J. Manuf. Sci. Technol., vol. 6, pp. 98-101, 2013. https://doi.org/10.1016/j.cirpj.2013.02.003
[29] J. Xu, Y. Ma, Q. Zhang, T. Sugahara, Y. Yang, and H. Hamada, "Crashworthiness of carbon fiber hybrid composite tubes molded by filament winding," Compos. Struct., vol. 139, pp. 130-140, 2016. https://doi.org/10.1016/j.compstruct.2015.11.053
[30] G. Sun, Z. Wang, J. Hong, K. Song, and Q. Li, "Quasi static axial crushing behavior of filament wound CFRP and aluminum/CFRP hybrid tubes," Compos. Struct., vol. 194, 2018. https://doi.org/10.1016/j.compstruct.2018.02.005
[31] S. Shevtsov, I. Zhilyaev, S. H. Chang, J. K. Wu, J. P. Huang, and N. Snezhina, "Vacuum resin infusion for thin walled composite parts: Experimental and numerical study," Appl. Sci., vol. 10, no. 4, p. 1485, 2020. https://doi.org/10.3390/app10041485
[32] K. Abdurohman and M. Siahaan, "Effect of mesh peel ply variation on mechanical properties of E glass composites by vacuum infusion," J. Phys. Conf. Ser., vol. 1005, p. 012009, 2018. https://doi.org/10.1088/1742-6596/1005/1/012009
[33] S. Shevtsov, I. Zhilyaev, S. H. Chang, J. K. Wu, and N. Snezhina, "Multi criteria decision approach for vacuum infusion process layout design," Polymers, vol. 14, no. 2, p. 313, 2022. https://doi.org/10.3390/polym14020313
[34] A. Hindersmann, "Overview of infusion processes," Compos. Part A Appl. Sci. Manuf., vol. 126, p. 105583, 2019. https://doi.org/10.1016/j.compositesa.2019.105583
[35] F. J. Hurtado, A. S. Kaiser, A. Viedma, and S. Díaz, "Vacuum infusion of laminated composites with different fiber orientations: Numerical study," J. Reinf. Plast. Compos., vol. 34, no. 3, pp. 196-212, 2015. https://doi.org/10.1177/0731684414566361
[36] P. J. Novo, J. F. Silva, J. P. Nunes, and A. Marques, "Pultrusion of fiber reinforced thermoplastic pre impregnated materials," Compos. Part B Eng., vol. 89, 2016. https://doi.org/10.1016/j.compositesb.2015.12.026
[37] A. Memon and A. Nakai, "Mechanical properties of jute spun yarn/PLA tubular braided composites by pultrusion," Energy Procedia, vol. 34, pp. 818-829, 2013. https://doi.org/10.1016/j.egypro.2013.06.818
[38] P. Mihai, "Stiffness properties of pultruded polyester plate elements," Bull. Polytech. Inst. Jassy, 2013.
[39] Hartono, M. Rifai, and H. Subawi, "Optimization of composite repair using 5H satin dry glass fabric and epoxy resin via vacuum bagging," J. Phys. Conf. Ser., vol. 739, p. 012052, 2016. https://doi.org/10.1088/1742-6596/739/1/012052
[40] A. Harper, "Reusable vacuum membranes for composite manufacturing," Reinf. Plast., vol. 60, no. 6, pp. 380-386, 2016. https://doi.org/10.1016/j.repl.2016.09.005
[41] P. Malek and D. Walczyk, "Silicone rubber properties during consolidation/curing of composites using specialized elastomeric tooling," J. Manuf. Sci. Eng., vol. 138, 2015. https://doi.org/10.1115/1.4030432
[42] J. Santa, J. D. Vanegas Jaramillo, and I. Patiño, "Mechanical characterization of RTM composites: Effect of fiber content, strain rate and orientation," Lat. Am. J. Solids Struct., vol. 13, pp. 344-364, 2016. https://doi.org/10.1590/1679-78252252
[43] P. A. Sreekumar, J. M. Saiter, K. Joseph, G. Unnikrishnan, and S. Thomas, "Electrical properties of short sisal fiber polyester composites fabricated by RTM," Compos. Part A Appl. Sci. Manuf., vol. 43, no. 3, pp. 507-511, 2012. https://doi.org/10.1016/j.compositesa.2011.11.018
[44] J. R. Hutchinson and P. Schubel, "Simulation of light resin transfer molding: Fabric permeability, compaction, and wind turbine blade case study," J. Reinf. Plast. Compos., vol. 33, pp. 1237-1257, 2014. https://doi.org/10.1177/0731684414527806
[45] J. Porto, M. Letzow, E. dos Santos, S. Amico, J. Avila Souza, and L. Isoldi, "Computational modeling of RTM and LRTM processes for complex geometries," Rev. Eng. Térmica, vol. 11, p. 93, 2018. https://doi.org/10.5380/reterm.v11i1-2.62007