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Experimental Characterization of Glass/ Carbon Hybrid Composite Reinforced by SiO2 Nanoparticles

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Keywords:
Delamination; Fiber pulled out; Fiber orientation; Glass-carbon hybrid composites; SiO2 nanoparticles.

Highlights:

- *Manufacturing glass/carbon hybrid composite materials using Vacuum Bag and Curing Technique.*
- *The mechanical properties of laminates (carbon and glass) with and without nano-SiO2 were experimentally measured using a strain gauge.*
- *The effect of adding silica oxidize on mechanical properties with tensile and three-point bending test.*
- *Hybrid composite materials were improved when adding 2 wt.%. of nano-SiO2 to the epoxy.*

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Abstract: The proven optimal stacking sequence of a glass/carbon hybrid composite and the effects of longitudinal fibers orientation and the incorporation of SiO_2 nanoparticles were carefully investigated in this work. For the first time, the present research explores the effects of adding silicon dioxide (SiO_2) nanoparticles on the tensile and flexural strength characteristics of glass-carbon hybrid composites with varying thicknesses and stacking sequences. Three fiber orientations were considered, i.e., 0°, 45°, and 90°, and SiO_2 nanoparticles as epoxy reinforcement. The infusion procedure was used to fabricate the hybrid laminates. To understand and analyze the impacts of fiber orientation and SiO_2 nanoparticles, mechanical parameters, such as tensile and flexural strength, were evaluated. The results showed that increasing plate thickness and the SiO_2 nanoparticles boosted tensile and flexural strengths. The bending force was increased by 80.5% when 2 wt.% SiO_2 nanoparticles were added to the epoxy for composites with 8 layers. For composite with 12 layers, the bending force increased by 62%.

التوصيف التجريبي لمركب هجين الزجاج والكربون المقوى بالجسيمات النانوية SiO2

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الخلاصة

في هذا البحث تمت دراسة تأثير اضافة جزيئات ثاني أكسيد السيليكا النانوية إلى طبقات هجينة من الزجاج/الكربون الي الايبوكسي النقي وبنسبة وزنية ٢٪ وكذلك تأثير عدد طبقات الزجاج والكربون على سلوك الشد والانحناء. إن دراسة تأثير جزيئات ثاني أكسيد السيليكون (SiO_2) النانوية على خصائص مركبات هجين الزجاج والكربون ذات السماكات المختلفة وتسلسلات التراص تعتبر فريدة من نوعها. تم أخذ ثلاثة اتجاهات رئيسية للألياف (٠°، ٤٥°، و٩٠°)، كما تم استخدام تقنية الاكياس المفرغة لتصنيع المركبات الهجينة. لفهم وتحليل تأثيرات اتجاه الألياف والجسيمات النانويةSiO_2 ، تمت دراسة قوة الشد والانحناء في العديد من التجارب. أظهرت النتائج أن زيادة سماكة الصفائح ووجود الجسيمات النانوية SiO_2 عززت قوة الشد والانحناء، إذ إن قوة الانحناء زادت بنسبة ٨٠٪ للصفائح ذات الثمانية طبقات، بينما زادت قوة الانحناء بنسبة ٦٢٪ للصفائح ذات الاثنا عشر طبقة.

الكلمات الدالة: الانفصال، الالياف المسحوبة، اتجاه الالياف، هجين الزجاج /الكربون، جزيئات SiO2النانوية.

1.INTRODUCTION

The composite material, fiber-reinforced plastic (FRP), is made of fibers and a polymer matrix. FRP composites are often employed in various structural applications that frequently call for sustained load exposure while in service because of their outstanding stiffness and specific strength. For these particular applications, it is vital to understand the significance of enhanced fracture toughness in composite materials. Epoxy undergoes a metamorphosis into an amorphous, heavily cross-linked material throughout the polymerization process. Epoxy polymers' microstructure influences several beneficial characteristics, such as high modulus, failure strength, and reduced creep. However, it is important to be aware of a possible downside to this quality. To be more precise, the epoxy polymer may show a comparatively greater level of brittleness and less resistance to fracture initiation and propagation, which could negatively impact how well FRP composites that use these fragile epoxy matrices fracture overall. Fiber Reinforced Polymers (FRPs) may improve their mechanical qualities by adding secondary-phase fillers to the epoxy matrix, improving its properties. To enhance the characteristics of composite materials, a wide variety of multilayer, fibrous, micro-, and nano-sized particle fillers have been used [1, 2]. Improved failure and damage resistance are provided by hybrid composite materials created by mixing several reinforcing fiber types, such as carbon and glass fibers, or matrix particles, such as micro and nano silica and SiO_2 [3]. These composites have exceptional qualities, such as lowering prices and improving mechanical properties like stiffness and elastic modulus [4]. The epoxy may mix various fibers and add particles to create a synergistic combination of benefits while minimizing their drawbacks since lightweight structural materials are essential for cutting-edge technologies and complicated constructions, such as cars, airplanes, and enormous wind turbine blades, developing them with extraordinary strength and durability is a major problem for composite engineers [5]. Proving that hybridization did not synergistically impact tensile characteristics, Fischer et al. [6] disproved several earlier experiments. However, the tensile strength of hybrid composites decreased while the tensile failure stresses increased. It has been shown that adding carbon nanotubes to composites efficiently enhances their mechanical characteristics. According to Iwahori et al. [7], adding carbon nanotubes improved the mechanical properties of two- and three-phase composites. According to Salam et al. [8], adding two distinct functionalized multi-walled carbon nanotubes to epoxy composites enhanced their mechanical and thermo-mechanical characteristics. Different glass carbon ratios and the stages of the two phases' dispersion were examined by Manders and Bader [9]. As the relative quantity of carbon fibers fell and the carbon fibers were more finely scattered, they noticed a rise in the failure strain of the carbon phase. In the case of a glass carbon fiber/epoxy composite, the hybrid effect and strain increase of up to 50% were investigated. Under dynamic and static loading rates, a carbon/glass composite material with a total fiber percentage volume fraction of 30% demonstrated splitting and kinking [10]. Zhang et al. [11] investigated the mechanical characteristics of carbon/glass fiber hybrid composites made using the "wet layup" manufacturing method, which is not suggested for laminates of superior quality. To improve the mechanical properties of glass/carbon hybrid laminates, Murugan et al. [12] discovered that low-modulus glass fiber should be placed inside and high-modulus carbon fiber on the exterior. In another work, Murugan et al. [13] created an ideal layering configuration for epoxy-based glass/carbon hybrid composites.

They examined how fiber orientation affected tensile and flexural strength and other mechanical properties. Poyyathappan et al. [14] employed the hand layup technique to fabricate bidirectional carbon fiber reinforcement, glass fiber reinforcement, and carbon-glass hybrid laminates. They used the three-point bend method to assess flexural features. The results showed that hybrid composites had better flexural qualities than glass fiber-reinforced polymer (GFRP). When continuous glass/epoxy composites were exposed to transverse stresses, Brianqon et al. [15] noticed that the matrix would brittlely shatter and distort. Benzarti et al. [16] investigated the influence of glass fiber orientation on the properties of epoxy-based composite materials. The authors observed that unidirectional glass fiber-reinforced polymer composites were less prevalent in industrial applications due to their inferior transverse stiffness and fatigue strength than bidirectional glass fiber-reinforced polymer composites. Brocks and Cioffi [17] used dynamic analysis to investigate the effects of carbon fiber surface characteristics and interfacial adhesion variations on the flexural properties of structural composites. A hybrid kenaf/silica nanoparticle epoxy composite was created by Bajuri et al. [18] and tested using filler materials made of silica nanoparticles. The material's flexural and compressive properties were enhanced by a 2% volume addition of silica nanoparticles. For epoxy matrix composites reinforced with unidirectional E-glass, Wang et al. [19] examined how the fiber orientation affected the Young's modulus. The researchers found that the elastic modulus of the composites was significantly affected by the angles of the fiber direction, which varied between 0° and 90°. Epoxy composites reinforced with glass and carbon fibers were examined by Dong and Davies [20] for their compressive and flexural properties. Their findings showed that failure happened more frequently during compression testing and that a decrease in bending modulus correlated with increased fiber density. Despite extensive prior research in this field, it is clear that a research void exists regarding nanoparticles' influence on composite materials' mechanical properties. Consequently, the primary objective of the present study was to investigate the impact of incorporating 2 wt.% SiO_2 nanoparticles into the epoxy matrix, particularly on the tensile and bending strengths of a hybrid glass/carbon composite with three primary fiber orientations: 0°, 45°, and 90°. The novelty of this study is the influence of adding silicon dioxide (SiO_2) nanoparticles on the tensile and flexural strength properties of glass-carbon hybrid composites. The experiment included adding SiO_2 nanoparticles, comprising 2% of the weight, to glass/carbon hybrid composites of different thicknesses and stacking sequences.

2.MATERIALS AND MANUFACTURING

2.1.Materials

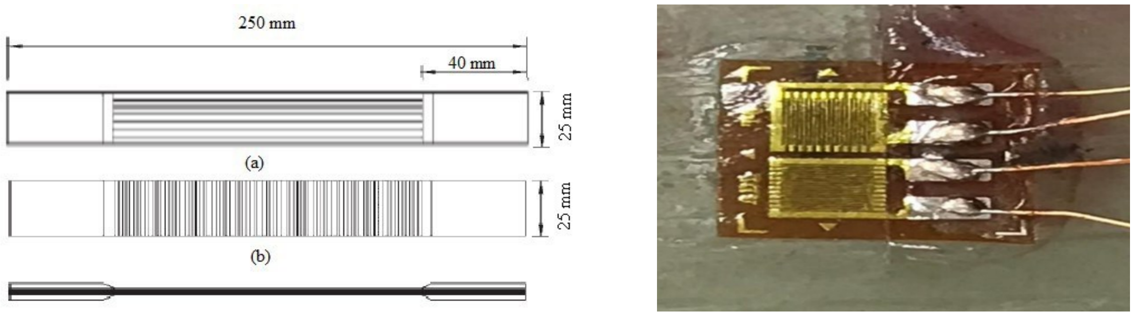
E-glass fiber and carbon fibers were selected as reinforcement materials. The epoxy resin and hardener, with a mixing ratio of 100:40 (resin: hardener), were used as a matrix; the matrix and fiber were supplied from DOST KIMYA Company, Istanbul/Turkey. A spherical silica oxide (SiO_2) nanoparticle, supplied by Nanografi Nanotechnology Company, Ankara, was used as a filler reinforcement. The main specifications of the used materials are shown in Table 1.

2.2.Manufacturing Hybrid Composites

Two groups of laminates were constructed. The first group consisted of two laminates created utilizing a 55% fiber volume fraction of unidirectional glass fibers/epoxy. Each laminate had eight layers with a 0-degree orientation angle. One laminate included nano-silica, while the other did not. Furthermore, two laminates were built using unidirectional carbon fibers/epoxy with a fiber volume percentage of 50% and eight layers at an angle of 0 degrees. One carbon fiber laminate, like the glass fiber laminates, included nano-silica, whereas the other did not. These laminates were created particularly to study mechanical properties, such as longitudinal modulus (E_1), transverse modulus (E_2), in-plane shear modulus (G_{12}), and Poisson's ratio (v_{12}). Figure 1 depicts the experimental setup and laminate configurations. The second group consisted of hybrid samples with 2 wt.% SiO_2 nano-silica-containing resins, glass fibers, and carbon fibers, with varying layer thicknesses, i.e., 8, 10, and 12 layers, and a fiber volume fraction of 53.33%, as shown in Table 2.

Table 1 Summary of the Unique Characteristics of These Hybrid Composites.

Types	Properties
Glass fiber reinforcement	Unidirectional (Glass Fabric Unidirectional-300 gr/sqm)
Carbon fiber reinforcement	Unidirectional (Carbon Fabric Unidirectional-300 gr/sqm Thermofixed)
Matrix (liquid)	Epoxy resin MGS (LR 285)
Hardener (liquid)	MGS (LH 287)
(Silicon Dioxide) nano	15-35nm, Purity 99.5+%, amorphous



(a) (b)

Fig. 1 (a) Stacking Setup, (b) Strain Gauge for Calculating E_1 and E_2.

Table 2 Stacking Sequence of Composite Laminates.

	Samples	Composite type	Stacking Sequences	No. of Layers	Thick. mm	Density g/cm^3	Weight g
First group	G	$[G/G/G/G]_s$	$[0^o/0^o/0^o/0^o]_s$	8	2	1.6576	1195.2
	GN	$[G/G/G/G]_s$	$[0^o/0^o/0^o/0^o]_s$	8	2	1.8413	1205.8
	C	$[C/C/C/C]_s$	$[0^o/0^o/0^o/0^o]_s$	8	2	1.4838	880
	CN	$[C/C/C/C]_s$	$[0^o/0^o/0^o/0^o]_s$	8	2	1.5056	888.8
Second group	S1	$[G/C/G/C]_s$	$[0^o/45^o/90^o/0^o]_s$	8	2.4	1.621	1037.6
	S2	$[G/C/G/C/G]_s$	$[0^o/45^o/90^o/0^o/45^o]_s$	10	2.65	1.662	1297
	S3	$[G/C/G/C/G/C]_s$	$[0^o/45^o/90^o/0^o/45^o/90^o]_s$	12	2.84	1.672	1556.4
	S1N	$[G/C/G/C]_s$	$[0^o/45^o/90^o/0^o]_s$	8	2.42	1.657	1037.6
	S2N	$[G/C/G/C/G]_s$	$[0^o/45^o/90^o/0^o/45^o]_s$	10	2.66	1.690	1297
	S3N	$[G/C/G/C/G/C]_s$	$[0^o/45^o/90^o/0^o/45^o/90^o]_s$	12	2.87	1.689	1556.4

**S: Plates without SiO_2 Nanoparticles, SN: Plates with SiO_2 Nanoparticles, G: Glass fibers, C: Carbon fibers, GN: Glass fibers with SiO_2 Nanoparticles, and C: Carbon fibers with SiO_2 Nanoparticles*

Many techniques exist for fabricating composite materials, each possessing distinct advantages and disadvantages that render them most suitable for specific applications. Regardless of the laminated material type used in this investigation, samples were prepared using the vacuum approach. The vacuum bag technique ensures robust consolidation by evenly applying clamping pressure to the surface. It enables the creation of samples in various forms, measurements, and sizes, with an amazing bubble-free quality of almost 99% [21]. A manual procedure was used to establish a uniform lamination across the glass and carbon plies in the correct stacking sequence. On top was a peel ply, a unique material designed to inhibit adhesion between the plate and infusion mesh. Before turning on the vacuum apparatus, the resin's specialized intake and outlet tubes were tightly closed. Employing the pressure gauge to keep the vacuum pressure at 760 mmHg for 30 minutes, a leak-free vacuum bag was obtained. The resin was added to the vacuum bag after the base temperature reached 80 degrees Celsius. Figure 2 shows the stages of manufacturing laminates at the beginning of the 15-hour curing process after the tubes were firmly closed to ensure optimal resin absorption between the fibers. As shown in Fig. 3 (a), a SONICS device that uses ultrasonic nanoparticle dispersion was used to mix the resin and nanoparticles for laminates, including SiO_2 nanoparticles. The high-pressure vacuum was used to remove the bubbles during the process, as shown in Fig. 3 (b). This tool made it easier for the nanoparticles to be distributed evenly throughout the resin.

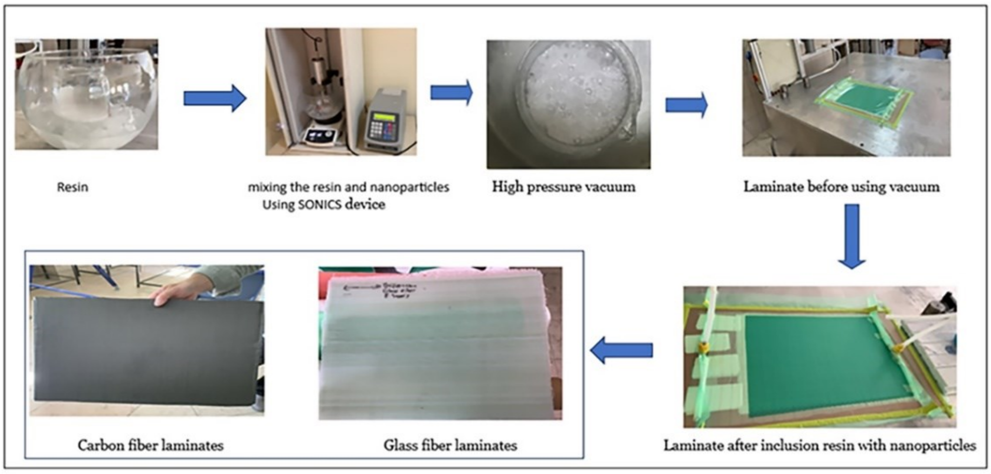


Fig. 2 Stages of Manufacturing Laminates.

(a) **(b)**

Fig. 3 (a) Ultrasonic Procedures for Small and Medium-Volume Applications, (b) Vacuum with High Pressure.

2.3.Test Specimen Preparation

Using a DIAMANT RUBI cutter, specimens for mechanical testing were produced from the composite plates, as shown in Fig. 4. Tensile test specimens were manufactured in accordance with ASTM D3039 [22]. Glass/resin material was used to bond the end of tensile samples. The dimensions of these specimens were 250 mm long and 25 mm wide, as shown in Fig. 5 (a). Bending test specimens with dimensions of 100 mm length and 10 mm width were made in accordance with the ASTM D790 standard [23], as illustrated in Fig. 5 (b).

Fig. 4 A Diamond Rubi Cutter.

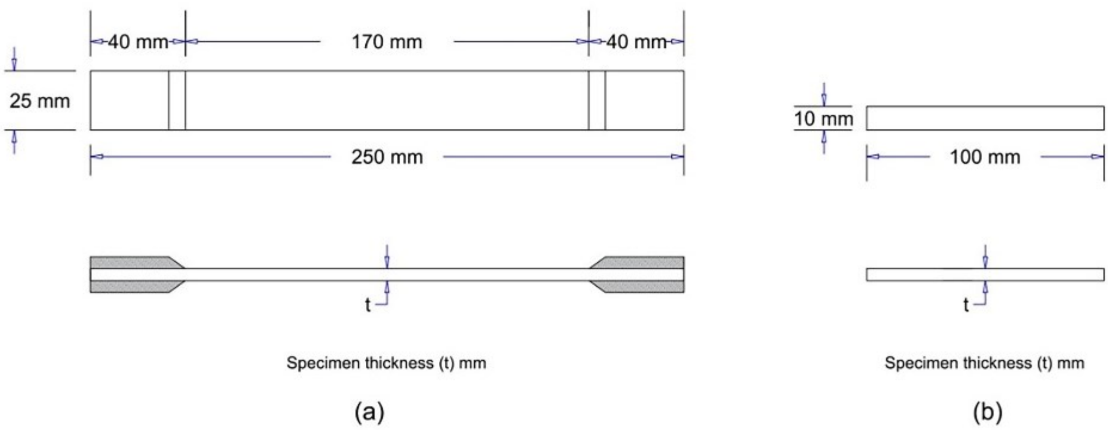


Fig. 5 Dimensions of Test Specimens for (a) The Tensile Test ASTM D3039 and (b) The Bending Test ASTM D790.

2.4.Tensile Test

The tensile experiments were divided into two groups. Firstly, tensile tests were conducted to measure the engineering constants, namely E_1, E_2, G_{12}, v_{12}, and density, for epoxy carbon and glass laminates individually with and without SiO_2 nanoparticles. In the second group of tensile tests, the mechanical properties, such as tensile strength, modulus of elasticity, and strain, were measured for glass/carbon composites with and without SiO_2 nanoparticles. All the tensile experiments were performed on a Shimadzu device with a load cell rated at 100 kN, as shown in Fig. 6 (a). The testing procedure included using a cross-head velocity of 2 mm/min. Fig. 6 (b) shows the tensile specimen used in the present study.

(a)

(b)

Fig. 6 (a)Tensile Test Using SHIMADZU Universal Testing Machine with a Force Capability of 100 kN, (b) Tensile Test Specimens.

2.5.Three Points Bending Test

The experiments were conducted utilizing a Shimadzu machine equipped with a 100 kN load cell and operated at a 1 mm/min loading rate, as depicted in Fig. 7 (a). The specimen was supported freely by a beam throughout the test, and the load was delivered to the center of the specimen. All tests were conducted at room temperature. Figure 7 (b) depicts the specimens utilized for the flexural test. Eq. 1 was used to calculate the flexural modulus.

$$E_F = mL^3/4bt^3 \quad (1)$$

where:

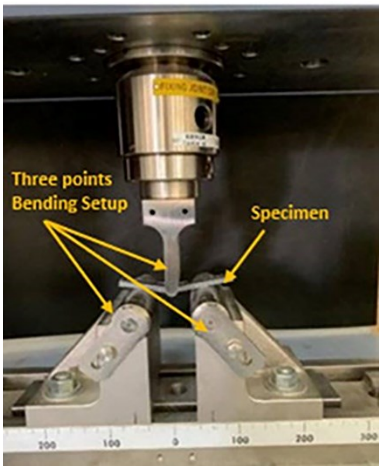
E_F = Flexural modulus (GPa),

m = Slope of the tangent to the initial straight-line portion of the load-deflection curve,

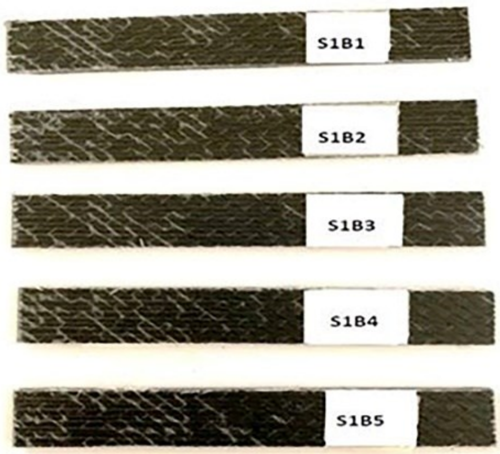
L = Support span (mm),

b = Width of beam tests (mm),

t = Thickness of beam tests (mm).



(a)



(b)

Fig. 7 (a) Three-Point Bending Test, (b) Three-Point Bending Test Specimens.

3.RESULTS AND DISCUSSIONS

3.1.Tensile Results

As mentioned above, two groups of tensile experiments were conducted. Table 3 shows the first group's results, which concerned measuring the engineering constants, namely E_1, E_2, G_{12}, v_{12}, and density. Table 3 shows how the engineering constants of epoxy/glass fiber composites changed when silica nanoparticles were added. Those results have a good correlation with the findings of [24]. Table 3 shows that v12 was the parameter that changed the most when SiO_2 was added, followed by E_2. At the same time, E_1 was the parameter least affected by adding the nanoparticles because the tensile force and the fiber direction are in the same direction. Adding SiO_2 nano-silica to the epoxy/carbon fiber composite has a much bigger impact on its engineering constants than adding SiO_2 nano-silica to the epoxy/glass composite, as shown above. These engineering constants of epoxy/glass fiber composites were increased to those of epoxy/carbon fiber composites, except for v_{12} because glass fiber provides good strength and toughness; however, it is generally less strong and stiff than carbon fibers. While carbon fiber is known for its exceptional strength-to-weight ratio and high stiffness, it also has excellent tensile strength and is stronger and more rigid than glass fiber [25]. In terms of density, glass fibers are denser than carbon fibers, which means they contribute more to the total weight of the composite material.

Table 3 Glass and Carbon Fiber Mechanical Properties.

Sample	Material	E_1 GPa	E_2 GPa	G_{12} GPa	v_{12}	Density g/cm³
$G[0^o]_8$	Pure Epoxy / Glass	31.80	10.95	4.27	0.21	1.6576
$GN[0^o]_8$	Epoxy/Glass with SiO_2 nanoparticles	33.36	13.41	4.48	0.26	1.8413
$C[0^o]_8$	Pure Epoxy / Carbon	99.44	6.27	4.03	0.24	1.4838
$CN[0^o]_8$	Epoxy / Carbon with SiO_2 nanoparticles	101.60	6.41	4.12	0.30	1.5056

Figure 8 shows the tensile results of the second group of experiments, which investigated the effect of SiO_2 nanoparticles on the mechanical properties of the carbon/glass fiber hybrid composites. It can be seen clearly from Fig. 8 that adding SiO_2 nanoparticles increased the load in all the specimens for all the layers. This outcome is ascribed to the influence of SiO_2 in enhancing the properties of the epoxy. As a result, the nanoparticle is considered a filler, which fills the voids that may be produced during the manufacturing of the composites and thus prevents the formation of stress concentration, which prevents the initiation of cracks [26], or these nanoparticles act as inclusions to prevent crack propagation [27]. Those results have a good correlation with the findings of [17].

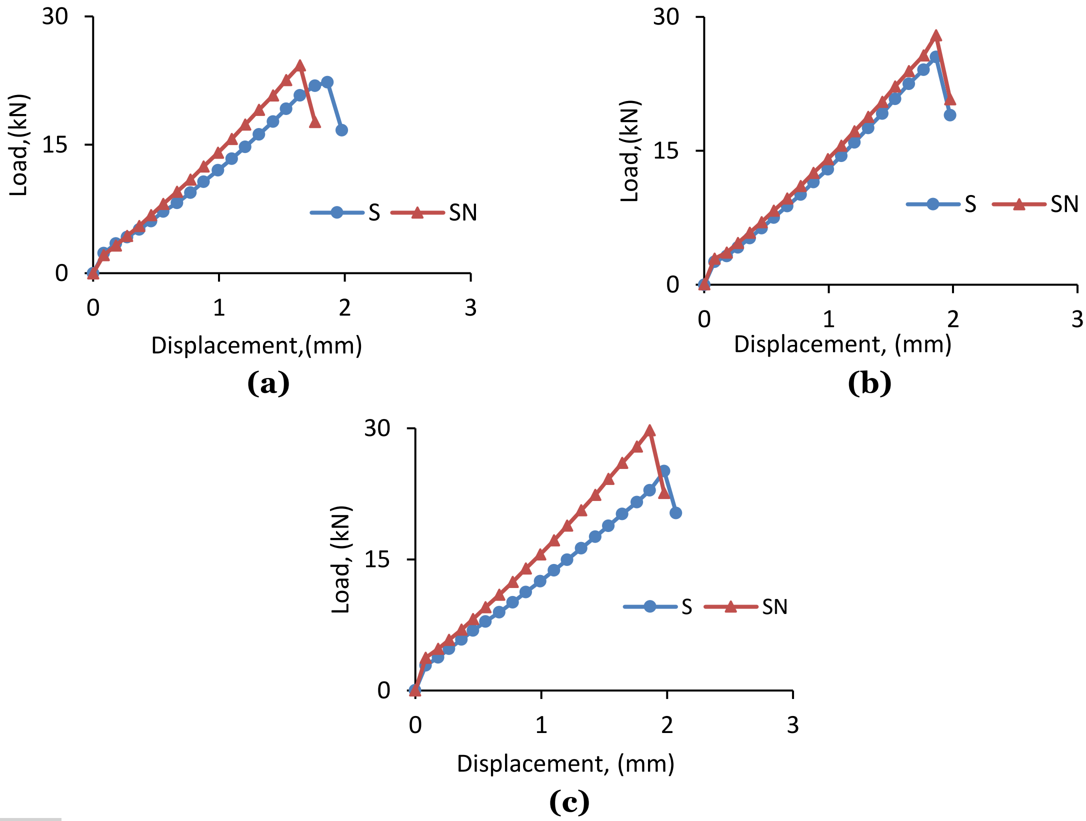


Fig. 8 Effect of Adding SiO_2 Nanoparticles on the Force-Displacement Tensile Test (a) 8-Layers (S1 and S1N), (b) 10-Layers (S2 and S2N), and (c) 12-Layers (S3 and S3N).

Table 4 presents the mechanical properties of hybrid laminates, comparing those with and without SiO_2 nanoparticles. These properties encompass the modulus of elasticity, maximum load, and maximum tensile stress. As evident from Table 4, including nanoparticles in glass/carbon hybrid composites resulted in notably superior mechanical properties to composites without nanoparticles. This result is similar to the results of [28] in terms of tensile strength behavior. Figure 9 shows photographs of the failure specimens with and without SiO_2 nanoparticles. Figure 9 shows the specimens' failure mode, consisting of multizone matrix fractures, pulled-out fibers, and fractures in glass and carbon fibers.

Table 4 Mechanical Properties of Hybrid Laminates at Tensile Test

Samples	Modulus of elasticity E1(GPa)	Maximum tensile load (N)	Maximum tensile stress (MPa)
S1	10.93	22442.68	374.05
S1N	11.75	24304.92	405.08
S2	11.07	26497.91	399.97
S2N	11.67	27953.25	421.94
S3	12.11	25090.06	352.14
S3N	14.65	29779.35	417.96

(a) **(b)**

Fig. 9 Tensile Specimens after Failure: (a) S1 (without SiO_2 Nanoparticles), (b) S1N (with SiO_2 Nanoparticles).

3.2.Bending Results

There is a considerable influence of glass fibers, carbon fibers, and silica nanoparticles on the strength of hybrid composite materials and the promotion of the bending strength as the number of layers increases. Figure 10 shows the load-displacement curves with and without 2 wt.% SiO_2 nanoparticles exhibit comparable linear behavior until reaching the maximum load, where the specimens begin to fracture. The range of recorded displacement was from 0 to 15 mm, while the maximum applied force on laminates without SiO_2 nanoparticles was between 400 to 600 N. The maximum applied force on the laminates with SiO_2 nanoparticles was between 780 to 1000 N. This maximum force difference indicates how adding nanoparticles enhances composite strength. When silica nanoparticles SiO_2 were added to epoxy, the bond strength between the epoxy and the fibers increased. It also reduced voids by occupying nanoparticles in the place of voids, improving the composite materials performance; this result is a good agreement with [29]. Table 5 shows the maximum flexural load and flexural modulus. It is clear that all those parameters increased with the presence of SiO_2 nanoparticles. The data from Table 5 illustrate that the applied bending force was increased by 80.5%, 76.8%, and 62.6 % for glass/carbon composites with (S1 and S1N), (S2 and S2N), and (S3 and S3N), respectively, when 2 wt.% SiO_2 nanoparticles were added to the epoxy. Adding SiO_2 to the matrix fills the voids, lowering the stress concentration, increasing the interfacial bonding strength, and, as a result, increasing the crack propagation resistance, reducing the possibility of crack initiation, and improving the load transmission from the matrix to the fibers. Figure 11 shows the three points bending failure specimens with and without adding 2 wt.% SiO_2 nanoparticles, which is in line with [2, 30, 31].

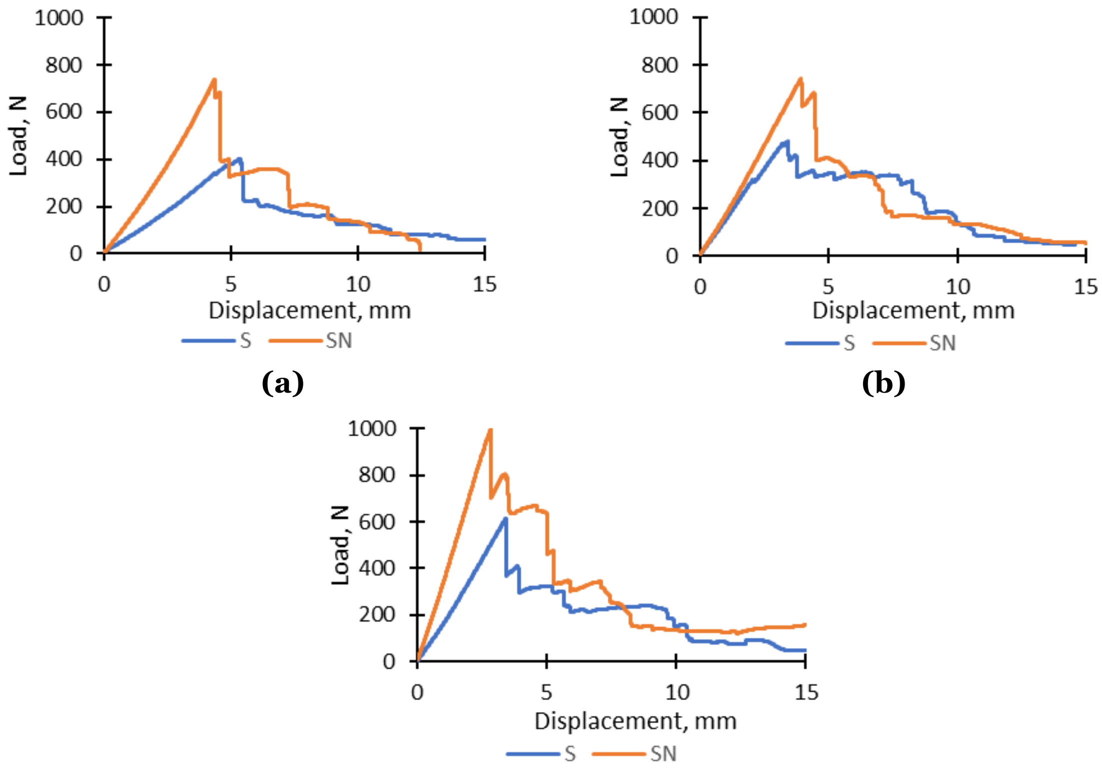


Fig. 10 Effect of Adding SiO_2 Nanoparticles on Force-Displacement Bending Test (a) 8-Layers (b) 10-Layers (c) 12-Layers.

Table 5 Mechanical Properties of Hybrid Laminates at the Bending Test

Samples	Maximum flexural load(N)	Flexural Modulus Ef (MPa)
S1	460.9947	40102.34
S1N	739.8553	66578.12
S2	480.9062	51031.25
S2N	665.5269	66699.21
S3	605.793	70585.93
S3N	986.8887	117386.72

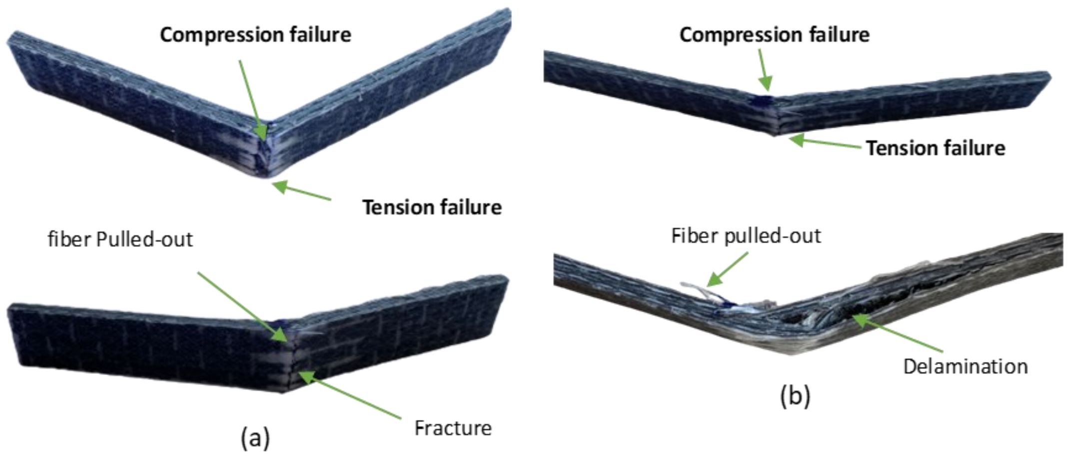


Fig. 11 Three Points Bending Specimens after Failure: (a) S1 (Without Sio_2 Nanoparticles), (b) S1N (With Sio_2 Nanoparticles).

4.CONCLUSIONS

The present research examined how fiber orientation, effective stacking sequence, and nano-silica inclusion affect the mechanical characteristics of glass/carbon hybrid composite plates. The experimental findings clearly showed that the hybrid composite had a considerable influence, depending on the specimen thickness, fiber orientation, and the presence of hybrid nano-silica resin. Tensile and bending strength tests were performed under semi-static loading conditions on the test specimens manufactured according to ASTM standards. The most obvious findings to emerge from this study are:

1- Incorporating SiO_2 nanoparticles into a resin matrix significantly impacted the mechanical properties of hybrid composites with a specific stacking sequence, i.e., 0°, 45°, and 90°.
2- The hybrid composites reinforced with SiO_2 exhibited substantial enhancements in tensile and bending stresses. When 2% wt. SiO_2 nanoparticles were added to the epoxy, the applied bending force increased by 80.5%, 76.8%, and 62.6 % for composites with 8, 10, and 12 layers, respectively.
3- Adding SiO_2 increased the maximum tensile load by about 19% in the laminates with 12 layers, whereas the maximum bending load increased by approximately 80% in the laminates comprising 8 layers.

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