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Mechanical PropertiesInvestigation of Unidirectional Woven Carbon Fiber Reinforced Epoxy Matrix Composite

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Abstract

In this study, the mechanical properties of an epoxy and unidirectional woven carbon with fiberglass composite were experimentally investigated. When preparing the composite samples, American Society for Testing and Materials (ASTM)standard was used. Tensile, impact and flexural test were conducted to investigate the mechanical properties of the new produced epoxy Unidirectional Woven Carbon and Epoxy Fiberglass composites. The outcome showed that the strength of the produced samples increased with the increase in the number of unidirectional woven carbon layers added. Two methods were utilized: (1) woven carbon composite with glass fiber (2) woven carbon composite). The two methods of composite were compared with each other. The results explained that woven carbon composite had higher mechanical resistance. While in impact test the toughness of the sample increased with adding layers of mixture of Fiber glass with unidirectional woven carbon and epoxy.

Keywords: *UDWC, Epoxy, Fiber glass, Composite material, Mechanical properties.*

1. Introduction

Basic composite materials consists of two specific planned materials. The primary benefit of composite materials is that the cost of this kind of materials is low .Production of fabric and covered metal instruments heavily relies on various composites [1]. Polymer composite materials are the lightest and have the higher modulus comparing with simple structure, even in some cases, the delamination reduces the mechanical properties of the known fiber reinforced compounds[2].

The latest wide-body twin-engine passenger aircraft now increasingly depend on composite materials, while smaller narrow-bodies (e.g. the Bombardier C Series/Airbus A220) are gaining traction. During the production of machine elements, drilling is still necessary for the assembly of sub-sections in the manufacturing of composite aircrafts utilizing mechanical fasteners [3].Carbon fiber composites are commonly used. That is due to simplicity of fabrication (even for components with complex shapes) and ease of orientation. The simplicity of fabrication and orientation allows designers to orient stiffness and strength in desired directions. Due to these factors, woven fiber composites are often less expensive than other types of composites[4].

For the process of fabricating composite from epoxy resin with fibers, several manufacturing techniques are available. Manufacturing techniques such as: manual lay-up technique, distillation, pultrusion filament winding, vacuum bag forming, and resin transfer molding. The hand lay-up technique is preferred for this work, because this technique is simple and powerful[5].

Woven fabric composites have advantages

such as good integration, compatibility and balanced properties in the fabric plane. Although layers of glass woven fabric are preferred in practice, additional layers are required to achieve the desired design strength. This happens in a larger nominal size, which increases the weight of the component/structure. Also, the additional layers make the structure commonly known in structural applications e.g. vehicles, aircraft, yachts, and civil structures [6].

Bhargav, et, al., (2021) prepared a composite by epoxy in addition with hardner, jute fiber (0/90 oriented) with 760 GSM and titanium dioxide TiO2 filler particles [7]also woven jute mat, Araldite LY556 epoxy resin and HY951 hardener based on Triethylenetetramine Ltd (TETA) by using hand lay-up technique and this method was adopted by 10:1 epoxy for curing. For an ASTM D3039-79 they performed tensile testing on a UTM with a dumbbell-shaped specimen and a crossover speed of 2 mm/min. For ASTM D790 bend test was adopted with 1.5mm/min.

S2-glass-woven/reinforced epoxy, woven IM7-graphite/reinforced epoxy, and woven S2-glass-IM7-graphite fiber/epoxy were used for researching purposes by [8]. Vacuum Assisted Resin Transfer Molding (VARTM) technology was used to stack plain-woven fill-warp fabrics together and the composite was manufactured and designed by EDO Fiber Innovations into (101.6 x 101.6) mm sheets, the specimens were cured at 177 °C.

A 0.3 mm thickness E-glass fabrics as reinforcement was used by [9] and epoxy with its hardener R101 and H101 as a matrix was used respectively. A rectangular volume was produced for conducting tensile tests using ASTM D638 (165x19x4mm) and ASTM D790 (130x12x4mm) for conducting flexural testing. That is to optimize the glass fibers weight fractions.

The epoxy resin type (WSR618) as the matrix was used by [10] with benzene dimethylamine as the resin-curing agent and butyl phthalate as the hardener. The layer-by-layer manual stacking process using room temperature vacuum technology and negative pressure curing was used to prevent delamination and cracks between layers.

E-glass and carbon fibers were used as reinforcements and epoxy as matrix material by [11]. Epoxy resin and Tri Ethylene Tetra Amine (TETA) hardener were supplied by Atul Ltd. The production of composites Glass/Carbon fiber/Epoxy based hybrid composites were made by using vacuum bag process trough changing both the reinforcements in terms of weight percentage of 15%, 30%, 45% and 60% fiberglass and carbon fiber in 40% epoxy matrix. The study outcome showed that the mechanical properties of carbon fibers were improved as the fibers reinforcement content increased in the matrix material.

[12]used Twill -glass fiber, aramid twill fiber, monocoque carbon fiber, unidirectional glass and unidirectional carbon fiber. An epoxy resin (MGS L285) was mixed with a solid (HGS L285) in a volume ratio of 50/100. The compound was made by a manual laying process. The composites were cured at 75°C in an oven after curing at room temperature for 24 h. The steel plates were stacked on the edges of some samples to prevent breakage. The carbon fiber reinforced epoxy compound had better performance than the glass fiber reinforced epoxy compound. That is due to the unidirectional fibers reinforcing the epoxy composite.

Bhargav and Babu, 2021 produced LY556 and HY591 epoxy resin matrix [7], 0.4mm thick bidirectional jute fiber reinforced and S-glass fiber in weaving. The fabricating technique was applied by hand. ASTM-D3039 standard was used for tensile test. For impact test, Izod was conducted according to ASTM-D256 standard and three-point bend test according to ASTM-D790 standard the sample size (80X8X3) mm. The results of this research explained that high strength, toughness and stiffness with the combination of two different levels of fibers play a critical role in automotive and some aerospace application components.

In this study, composite materials which consists of epoxy, Unidirectional woven carbon and fiber glass are produced by using hand-lay-up technique. Also, the mechanical properties are determined by testing the specimens. Tests are Tensile, Impact and Flexural.

2. Experimental Study

2.1 Materials

In this study, the mechanical properties of carbon/fiberglass unidirectional woven epoxy are experimentally investigated. The characteristics of each material used are found.

2.1.1 Epoxy

In this investigation for preparation of the specimens, a type of "Master Protect 180"epoxy is used (a high build epoxy resin). This type of epoxy consists of two-component part A is as base and part B is as hardener. Mixing the two components is very critical by a thin stick for 2-3 minute. Table 1 shows the main characteristics of this epoxy resin.

Table 1,
chemical and physical properties of Master Protect180 epoxy

Parameter	Epoxy	Unit
Mixing ratio	3:1	%
Mixing density	1:5	g/cm3
Initial cure	24 at 25	Hours at°C
Final curing	7 at 25	days at°C
Working life	40	Minute

2.1.2. Unidirectional woven carbon (UDWC)

SikaWrap-230 C is a unidirectional woven carbon (UDWC) fiber fabric with mid-range strengths is used. SikaWrap-230 C is designed for installation using the dry application process. See Table 2 for more information about this type of carbon and Figure 1(a).

Table 2,
Mechanical and physical properties of unidirectional woven carbon

parameter	UDWC	Unit
Fiber density	1.82	g/cm^3
Filament diameter	21-22	µm
Tensile strength(MPa)	4	GPa
Tensile modulus (MPa)	230	GPa
Faber orientation	0	rad
Limit temperature	5-35	°C

(a) (b)

Fig. 1. (a) Unidirectional carbon fiber (b) Fiber glass.

2.1.3. Fiber glass

360 Direct Roving is a saline compatible with unsaturated polyester, vinyl ester and epoxy resin. 360 Direct Roving is designed for wire wrap, drip, and weave applications. 360 Direct Roving is suitable for use in pipes, pressure vessels, grates, profiles and roving woven diverters. Also, 360 Direct Roving is used in boats and chemical storage tanks. See Table 3 and Figure 1(b).

Table 3,
mechanical and physical properties of fiber glass.

Parameter	Fiber glass	Unit
Density	2.62	g/cm^3
Filament diameter	21-22	µm
Tensile strength	2673	MPa
Tensile modulus	81126	MPa
Shear strength	70	MPa
Limit temperature	15-35	°C

2.2. Fabrication of composite layers

Molds are needed. Molds are built by 3mm thickness plate has an internal rectangular hole 200mm by 100mm see Figure 2. For each test AutoCad2023is used for the purpose of designing the specimen with different standards, see figure3. A Computer Numerical Control (CNC) machine is employed for cutting the prepared composite specimens.

To know the amount needed of epoxy, the mold is filled with epoxy and the percentage of the UDWC with fiber glass are calculated .

For Tensile Sample

Volume = Area x thickness …(1)

V=2509 x 3 = 7.527 cm^3

Wight of sample = Density of epoxy x Volume …(2)

=1.5 x 7.527 =11.2905 gm

Volume= $\frac{11.2905}{1.5}$ = 7.527 cm^3

5% of UDWC = 0.3763cm^3

10% of UDWC = 0.7527 cm^3

15% of UDWC = 1.1290cm^3

3% of UDWC +3% OF FIBER GLASS = 0.2258 + 0.2258 = 0.4516cm^3

1.5% of UDWC = 0.1129cm^3

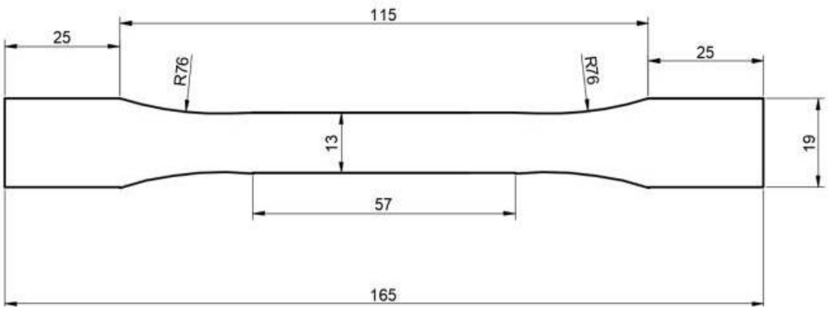
Impact Sample

Volume =16.10 x 0.3=4.83 cm^2
Wight of sample = 1.5 x 4.83 = 7.245 gm
Volume= 4.83 cm^3
5% of UDWC = 0.2415 cm^3
10% of UDWC = 0.483 cm^3
15% of UDWC = 0.7245 cm^3
3% of UDWC +3% OF FIBER GLASS = 0.1449 + 0.1449 = 0.2898 cm^3
1.5 % of UDWC = 0.0725 cm^3

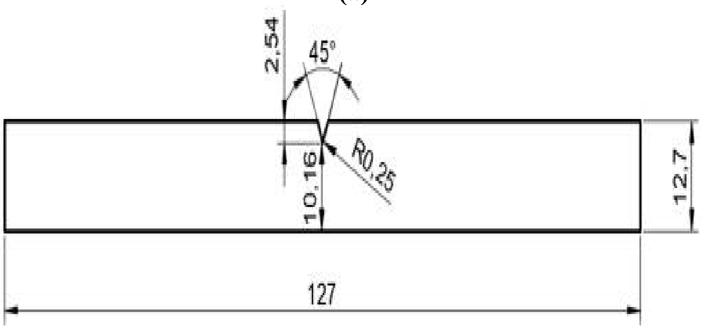
Flexural Sample

Volume=16.51 x 0.3=4.953cm^2
Wight of sample =1.5 x 4.953 =7.2495gm
Volume = 4.833 cm^3
5% of UDWC = 0.2416 cm^3
10% of UDWC= 0.4833 cm^3
15% of UDWC= 0.7249 cm^3
3% of UDWC +3% OF FIBER GLASS = 0.14499 + 0.14499 = 0.2899 cm^3
1.5 % of UDWC = 0.0724 cm^3

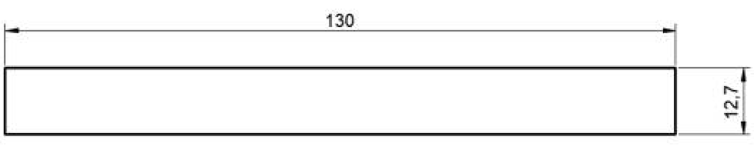
Fig. 2. The plate mold.



(a)



(b)



(c)

Fig. 3 AutoCAD drawing a) tensile test sample b) impact test sample c) flexural test sample Note, all dimensions are in mm.

Hand lay-up technique is used, layer by layer, for fabricating the new proposed composite materials (epoxy UDWC and fiber glass)in each sample a different layer from the others is conducted.

The first step to start conducting compound material is to prepare the mold, by using on backside a limpid paper and adopting a stick for all sides. Then in the second step the front of the mold is cased inside for ease emerging. Later on sticks is used for adopting, while in the third step, a layer of epoxy resin is used. After that in the fourth step the second layer which is unidirectional woven carbon is used. These steps are picked out in figure4. These steps are repeated for each composite specimen to produce all the specimens with the same components. One time for each percentage. That is because all the samples are from the same plate.

a. First step

b. Second step.

c. Third step

d. Fourth step

Fig. 4 steps of fabricating composite materials.

For the purpose of investigating mechanical properties of samples, three mechanical tests are conducted . The tests are: (1) tensile test (2) impact test (3) flexural test. In the next section the details of the mechanical investigations are explained in details.

3. Mechanical Tests and Results

The specimen is labeled. For the mechanical tests, three group of specimens are prepared. Group (A1-0, A1-1, A1-2, A1-3, A1-4, A1-5, and A1-6) for tensile tests, group (B1-0, B1-1, B1-2, B1-3, B1-4, B1-5, and B2-6) for impact tests and group (C1-0, C1-1, C1-2, C1-3, C1-4, C1-5, and C1-6) for flexural tests, as indicated in Table 4.

Table 4,
Labeling each specimen for the mechanical tests

Code of composite	Carbon %	Fiber glass %	Layers of composite
A1-0, B1-0, C1-0	0	0	Epoxy
A1-1, B1-1, C1-1	5	0	Ep*-C**-Ep
A1-2, B1-2, C1-2	10	0	Ep-C-Ep-C-Ep
A1-3, B1-3, C1-3	15	0	Ep-C-Ep-Ep-C-Ep
A1-4, B1-4, C1-4	3	3	Ep-C-Ep-F.g***-Ep
A1-5, B1-5, C1-5	3	1.5	Ep-C-Ep-F.g-Ep
A1-6, B1-6, C1-6	1.5	3	Ep-C-Ep-F.g-Ep

Noting that
*Ep refers of Epoxy, **C refers to Carbon, ***F.g refers to Fiber glass

3.1. Tensile test

In this test, ASTM D638 standard is utilized. A machine type of XHC-50 ring stiffness tester is employed to test samples. The machine has a software that shows all details about the test. The cross head is 5mm/min, worked with a 100KN load cell with advanced load control. Figure 5 shows two samples before testing.

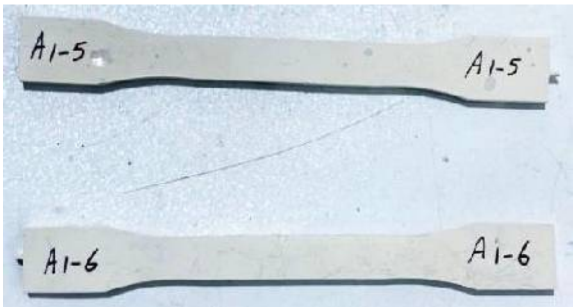


Fig. 5. Specimens tested in tensile.

3.2 Impact test

In this test, ASTM D256 is used see figure 6. A machine XJJD-50Seriesis used to conduct impact test. Charpy impact test is conducted for both metal and plastic. In summary, the details of load and energy are determined.

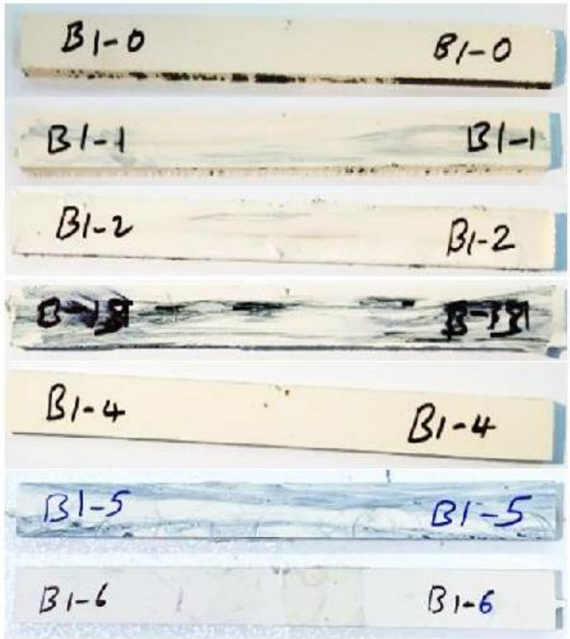


Fig. 6. Samples tested in impact.

3.3 Flexural test

This test is done by XWW-5KN by software all details are known using ASTM D790 see Figure7. The value of the bending units is determined. Seven samples are generated to perform this test and the average quality is calculated; the speed of the crosshead used is 5 mm/min with an extension length of 80 mm.

Fig. 7. Samples tested in flexural.

4. Results and discussion
4.1. Tensile test

As shown in Table 5 and the results of the samples for the tensile test are illustrated in figure8, the highest value of ultimate tensile stress is (168 MPa). That is reached in sample A1-4, which contains a mixture of fiberglass and UDWC. On the other hand, adding more layers of UDWC to the sample, the tensile strength also increases. This indicates that the difference in stacking sequence has little effect on the tensile strength. In addition, the table shows the modulus of elasticity for each sample and the highest one is A1-4 which contains tertiary epoxy, UDWC and fiberglass. This is another indication that shows that the rigid bond between this triple mixture is very high that leads to have the highest modulus of elasticity. Figure8 shows the relation between stress and strain, and figure 9 shows samples after testing.

From[13] Modulus of elasticity can be found as bellow:

$\sigma_{max}=P_{max}/(\text{Cross section area})$ …(3)

where: σ = tensile stress, MPa

P_{max} = maximum load prior to failure,

N A = average cross-sectional area, m^2

$\epsilon = \Delta L/L$ …(4)

Where;

€ = strain, unit less

ΔL = change in length (mm)

L = original length (mm)

Young's Modulus od elasticity (E) = σ/ €

…(5)

Where E is in MPa.

Modulus of elasticity will be found by equation 5, all parameters are known from equation 3& 4 subsequently.

Table 5,
Tensile test results

Composite Code	Load (N)	Stress (MPa)	Strain (mm)	Elongation (%)	E (MPa)
A1-0	415	10.05	18.02	7.5	0.55
A1-1	3460	74	5.8	0.83	12
A1-2	4260	107	13	1.23	8.2
A1-3	4620	121	23	1.18	5.2
A1-4	7670	168	5	11.77	33
A1-5	1130	23	3.8	9.6	6.05
A1-6	1380	32	2.9	7.89	11.03

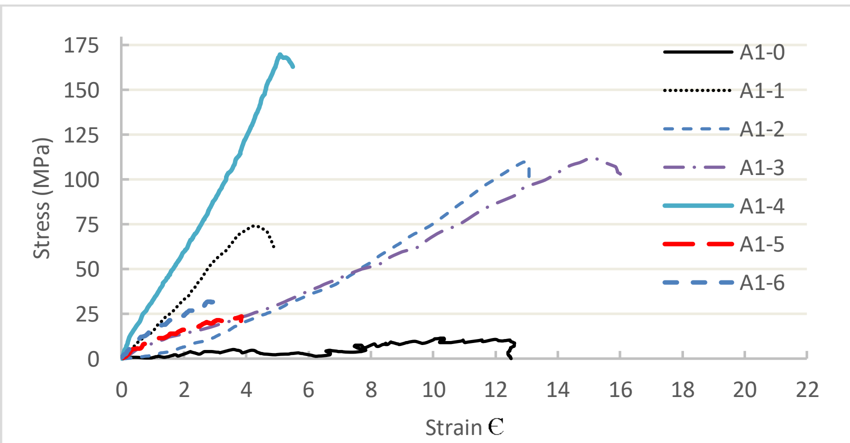


Fig. 8. Stress-Strain curves for experimental tensile tests of (A1-0, A1-1, A1-2, A1-3, A1-4, A1-5, and A1-6)

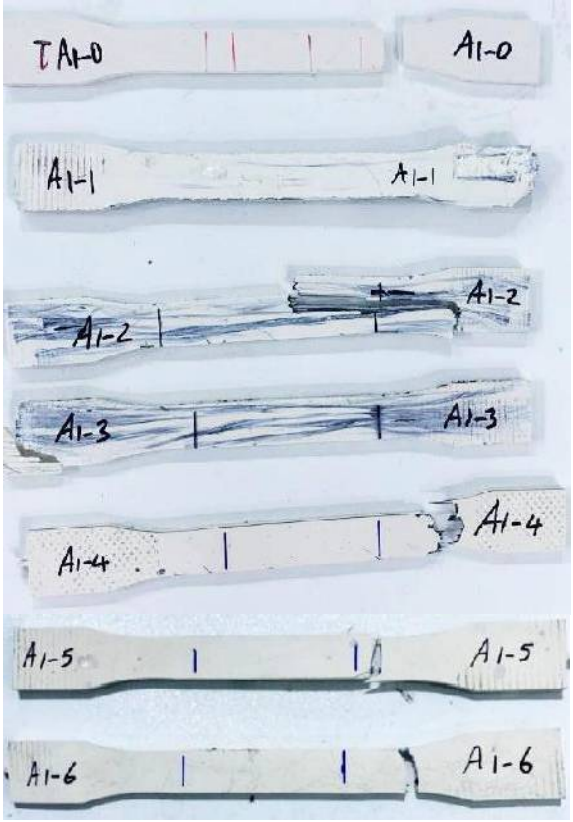


Fig. 9. Sample tested in tensile results.

4.2. Impact test results

Table 6 shows the impact testing results of unidirectional woven carbon fiber reinforced epoxy composites, as well as the fiber glass strength. As its seen from the tables the layers of UDWC increases the kinematic energy inside the composite samples increases too because of the rigid bond between the epoxy and UDWC fibers, samples after testing as shown in figure 10, and the results are shown in the Figure 11. The most extreme impact strength is 6.387 j because of having he most layer on it and having the highest toughness compared to others and surely because of having UDWC, that gives more ductility to the sample, and the fracture area is less. Moreover, both samples B1-2 and B1-4 gives approximately the results of strength. The results show that even adding a layer of fiber glass, can improve the toughness about 3% of the sample. This is a point that can be noted which has a good effect for increasing the toughness of the sample by this small range of fiber glass layers.

Table 6,
Impact testing results of unidirectional woven carbon fiber reinforced epoxy composites

Composite Code	Energy (Joule)
B1-0	0.103
B1-1	1.488
B1-2	2.757
B1-3	6.387
B1-4	2.059
B1-5	1.578
B1-6	0.867

Fig. 10. Impact testing samples.

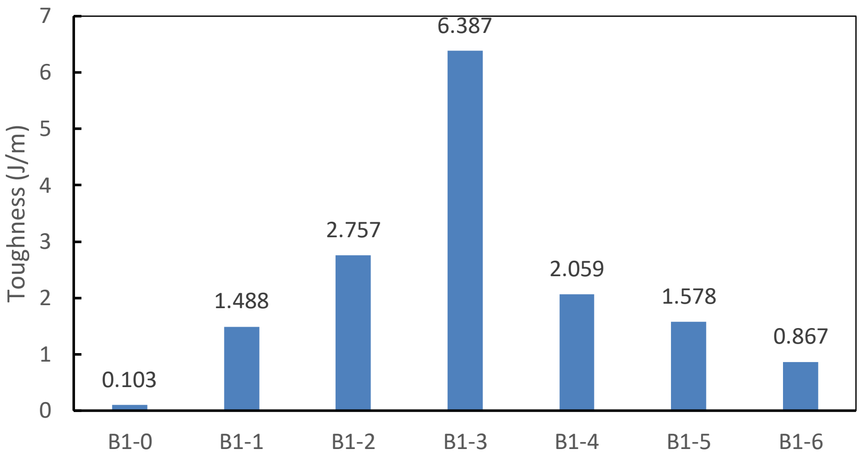


Fig. 11. Impact toughness for (B1-0, B1-1, B1-2, B1-3, B1-4, B1-5, and B1-6).

4.3 Flexural test results

The variance of the flexural strength with the percentage of UDWC and fiberglass is shown in Table 7. The flexure stress increased by this additional percentage, as well as the maximum (100 MPa) in the load (207 N) containing three layers of UDWC. The flexural behavior of the composite was increased by the interfacial bond between the UDWC and the matrix. And the combination of fiberglass and UDWC has an intermediate value of results which is (135N) with (65MPa). Also, about modulus of flexure sample C1-1 Has the highest value the reason is the bond of rigid strength between UDWC and the epoxy resin.

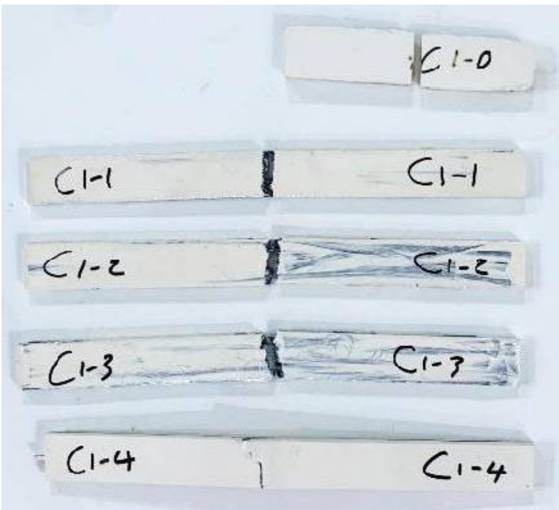


Fig. 12. Samples tested in flexural

From [13] flexural modulus will be found by:

$E_F = \frac{L^3\, m}{4\, bh^3}$ (6)

Were;

E_f = Flexural modulus (MPa),

L = Span length (mm)

b = Width of the sample (mm)

h = Thickness of the sample (mm)

m= Slope (N/mm)

Table 4,
Flexural testing results

Composite Code	Load (N)	Flexure Stress (MPa)	Flexure Strain	Flexural Extension	Flexural Modulus (MPa)
C1-0	43	20.9	0.064	15	32752
C1-1	118	57	0.054	10	349291
C1-2	141	68	0.033	8.3	252285
C1-3	207	100	0.0292	7	192992
C1-4	135	65	0.062	15	112467
C1-5	29.8	27.37	0.07	20.77	627
C1-6	25.0	22.99	0.06	15.89	3520

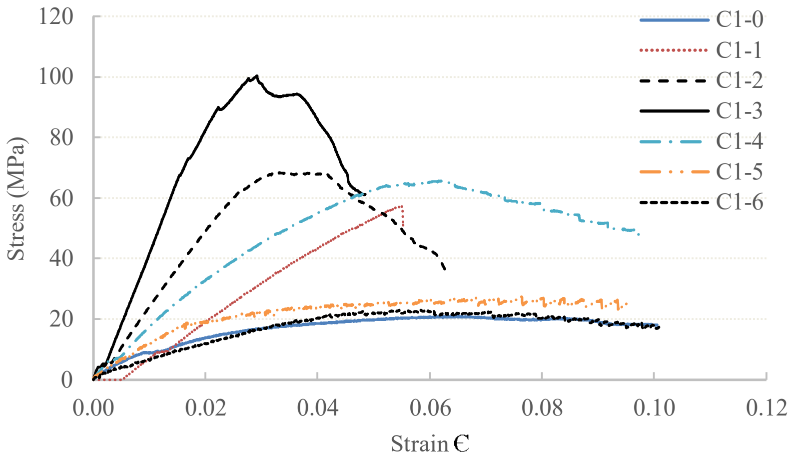


Fig. 13. Stress-Strain curves for flexures experimental tests of (C1-0, C1-1, C1-2, C1-3, C1-4, C1-5, and C1-6)

4. Conclusion

In this study, the mechanical properties of unidirectional woven carbon, fiber glass/ epoxy composite at different rate of layers were studied. The compression between flexural modulus and modulus of elasticity were theoretically found and clearly discussed. The following points can be concluded:

1- Adding more UDWC layers may increase mechanical properties such as tensile stress.
2- Tensile stress of all specimens varied (decreased) when fiber glass was added to the composite specimens, this variation happened in samples A1-4, A1-5 and A1-6 showed the maximum value when 3% UDWC and fiber glass in A1-4 sample when mixed together with epoxy resin.
3- The maximum value of Young's Modulus of elasticity were achieved within A1-4 specimen the reason is due to multiple layers and having much more composite material on in such as UDWC.
4- From impact test the sample B1-3 has the highest toughness energy, this increase in toughness because more layers of UDWC exists
5- The flexural modulus indicates the tendency of the samples. High value of flexural modulus was found with C1-1 sample in which it has the low weight and it has 10% of UDWC layers inside.
6- The achievement results from the triple mechanical tests shows that as much as the layers of UDWC added, the mechanical properties will be increased.

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دراسة الخواص الميكانيكية لمركب إيبوكسي معززة بألياف الكربون أحادية الاتجاه

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الخلاصة

في هذه الدراسة تم دراسة الخواص الميكانيكية للكربون المنسوج الايبوكسي أحادي الاتجاه مع مركب الألياف الزجاجية بشكل تجريبي. عند تحضير العينات المركبة، يتم استخدام معيار الجمعية الأمريكية للاختبار والمواد (*ASTM*). تم إجراء اختبار الشد والصدمة والانحناء للتحقق من الخواص الميكانيكية للمنتج الجديد الكربون المنسوج أحادي الاتجاه مع الإيبوكسيول مركبات الإيبوكسي أحادية الاتجاه المنسوجة المصنوعة من الكربون والألياف الزجاجية. لوحظ أن قوة العينات المنتجة تزداد مع زيادة عدد طبقات الكربون المنسوجة أحادية الاتجاه المضافة. إذا قارنت طريقتنا المركب مع بعضهما البعض (مركب الكربون المنسوج مع الألياف الزجاجية، مركب الكربون المنسوج)، فقد لوحظ أن مركب الكربون المنسوج يتمتع بمقاومة ميكانيكية أعلى بكثير، وبالتالي في اختبار التأثير يكون العكس بالعكس، تزداد صلابة العينة مع إضافة طبقات من خليط الألياف الزجاجية مع الكربون المنسوج أحادي الاتجاه والإيبوكسي.
