Experimental and Numerical Simulation of Impact Fracture Toughness of Polyphenylene Sulfide Basis Composite Material

***Prof.Dr.Najim A .Saad, ** Assist. Prof. Dr.Mohammed S. Hamzah, **Ahmed F. Hamzah**

***Babylon University, Engineering Materials College**

**** University of Technology Engineering Materials Department**

Abstract

This paper deals with experiments and numerical simulations of composite material with Polyphenylene sulfide matrix and carbon and glass fibres; the main goal is determine impact fracture toughness of composite materials and compare with numerical simulations, to predict the properties and the study effect of fiber type, number of layers and fiber orientation on the fracture toughness. For this purpose impact test and their computational simulations by ANSYS were carried out. The results show that the impact strength increases with the increase number of layers for both type of fibers, numerical simulation show good agreement with experimental results.

Key words: Polyphenylene sulfide, ANSYS, impact test, numerical simulation, fracture toughness

دراسة عملية ونظرية لتحديد متانة الكسر للمادة المركبة ذات الاساس من بولي فنيلين سلفايد

أ.د. نجم عبد الامير سعيد	أ.م.د. محمد صلاب حمزة	احمد فاضل حمزة
كلية هندسة المواد	قسم هندسة المواد	قسم هندسة المواد
جامعة بابل	الجامعة التكنولوجية	الجامعة التكنولوجية
07805303047	07801856260	07708777828
jasim_910@yahoo.com	dr.msh2013@yahoo.com	ahmeddesigner2005@yahoo.com

الخلاصة:

تم في هذا البحث دراسة مقاومة الصدمة للمادة المركبة المكونة من بوليمر بولي فنيلين سلفايد كمادة اساس مقواة بالياف من الكربون والزجاج، وقد تمت الدراسة عمليا وحسب المواصفات القياسية ونظريا بطريقة العناصر المحددة باستخدام برنامج (ANSYS) وقد تم دراسة عدد من المتغيرات وتأثيرها على متانة الكسر مثل نوع الليف ، عدد الطبقات وتوجيه الالياف ، بينت النتائج العملية زيادة واضحة في مقاومة الصدمة مع زيادة عدد الطبقات ولكلا نوعي الالياف المستخدمة في البحث ، كما ان التحليل النظري بين توافق جيد مع النتائج العملية .

Introduction:

Composites, in the past, have been mainly used for savings in secondary structures. With several advances made in understanding the behavior of composite materials, many fiber-reinforced polymer composite materials are finding increasing use as primary load-bearing structures and also in a wide range of high-technology engineering applications. The ability to tailor composites, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance, corrosion resistance, and lower manufacturing costs, makes them very attractive when compared with conventional metals. Of late there has been a trend towards lean weight vehicle structures that has paved the way for increased utilization of polymer composite materials in the automobile industry. The main drawback of composite systems is their inability to resist defect initiation and propagation when compared with metallic systems. Investigation in the past has shown that even low-energy impacts are capable of generating enough damage to cause significant reductions in their load-bearing capacity. [1]

The ability to resist defect propagation is characterized by the fracture toughness of the material. Fracture mechanics gives us a quantitative handle on the process of fracture in materials. Its approach is based on the concept that the relevant material property, fracture toughness, is the force necessary to extend a crack through a structural member. Under certain circumstances, this crack extension force (or an equivalent parameter) becomes independent of the dimensions of the specimen. The parameter can then be used as a quantitative measure of the fracture toughness of the material. [2]

Fracture toughness of fiber reinforced composite material is of great interest as well as its strength, because it is essentially important when fracture behavior of composites was investigated. For example, fracture mode of brittle matrix composites are strongly affected by the fiber fracture toughness as well as its interface toughness [3].

While many scientists have investigated the fracture toughness properties in various continuous fiber-reinforced composite materials there is no literature available on the fracture toughness properties dependent on impact test for carbon or glass fiber-reinforced composite materials, which can consider serious problem in a wide range of load-bearing engineering and industrial process applications primarily. Therefore, in this study, an attempt is made to determine the fracture toughness of continuous carbon and glass woven fibers composite material systems based on Polyphenylene sulfide as matrix as laminated composite materials with different fibers orientation and different number of layers experimentally and numerically by using finite element program code called [ANSYS 12.1].

Experimental:

The experimental work includes two stages: 1-preparation of thermoplastic composite material, 2-measuring it's in impact test.

1-Materials and Specimen Preparation:

The materials used in this study is cross ply woven (E-glass) fiber, unidirectional woven carbon fiber (type 300 C/60) are supplied by Sika Ypi Co.,Ltd / Turkey and Polyphenylene sulfide (PPS) polymer.

PPS material offer the broadest resistance to chemicals of any advanced engineering plastic. They have no known solvents below 392°F (200°C) and offer inertness to steam, strong bases, fuels and acids. A very low coefficient of linear thermal expansion, make these PPS products ideally suited for precise tolerance machined components. In addition, PPS products exhibit excellent electrical characteristics and are inherently flame retardant. [4]

To production of composite sheet, a carbon steel die shows in the figure (1) was made by using milling machine and grinded to the gives final product composite sheet dimensions are (4×250×250) mm which it cut later to suitable shape of specimens. The film stacking method was used to prepare the composite sheet. It consists of the following steps:

1- Preparation the die by covering it by aluminum foil to prevent adhesion with it faces then coat the aluminum foil by thermal grease (Lithium Grease) to prevent adhesion between polymer sheet and aluminum foil.
2- The fibers were arranged in the suitable angle and number of layers. PPS sheet with thickness of (3) mm was put under the fibers. Also another sheet of PPS with same thickness was put above the fibers and then the upper portion of die (punch) was fixed on the base portions (die)
3- Put the closed die in the thermal hydraulic pressing type (XLB-plate vulcanizer).Temperature on heating plates was adjusted to (300)^{o}C. This temperature degree is above the PPS melting point. The closed die remained under contact pressure until the temperature reach to (300)^{o}C and at this point apply the pressure for (30) min and it value equals 1.7 MPa (250psi). The die was cooled with water jet (5 L/min) at room temperature and during cooling processes the pressure is maintained to avoid distortion of composite sheet.

The procedure of this process was repeated to make a number of the composite sheets of different types. Different values of volume fraction are used are (6-32 %) as listed in the table (1).

2-Impact Test:

This test is performed according to (ASTM D256) at room temperature. Izod and Charpy impact tests are used for testing polymeric materials, Figure (2 a, b and c) shows standard specimen for impact test, the machine it used in the test and fixation of specimen respectively.

In this test, the calculation of the impact strength and fracture toughness depended on the calculation of the required energy for fracture. [5]

Impact strength is calculated from the following equation:-

$$G_c = \frac{U_c}{A} \qquad \text{…………………} (1)$$

Where:

G_c: Impact strength of material (J/m^2).

Uc: Absorbed energy (J).

A: cross- sectional area of specimen (m^2).

Fracture toughness, which describes the ability of a material containing a crack, to resist fracture, can be expressed as:-

$$K_c = \sqrt{G_c E} \qquad \text{………………….. } (2)$$

Where:

Kc: Fracture toughness of material ($MPa.m^{1/2}$).

E: elastic modulus of material (MPa).

ANSYS Simulation of Impact Test:

A 3D Finite Element model was created to simulate fracture test in ANSYS 12.1 Solving a numerical simulation was conducted based on laboratory conditions used in a practical test for the impact test where we were taking into consideration the shape and geometry of the sample process and the fixation method and the shape and geometry of the hammer. In this section, we will concentrate on two main aspects of this procedure.
Modeling the specimen and calculating the strain energy conducted simulations using ANSYS Explicit Dynamic Workbench as the following:

1-Material Properties:

The mechanical properties (Young's modulus, Shear modulus and Poisson's ratio) of the composite system used in this study are determined theoretically by using laminated theory of composite material, there are eight type of composite materials used and they vary in the number of layers and fiber orientation. Table (2) contains elastic constant of the composites materials of this work.

2-Geometry:

The model consists of three parts, are the fixed base which put the specimen on it, specimen as standard dimensions according to ASTM D256 and striker as shown in figure (3)

3-Applied Boundary Conditions:

The striker was modelled as rigid body with defined velocity at the moment of impact as shown in figure (4): by the formula: [6]

$$v = \sqrt{2gh} \qquad \text{................ (3)}$$

Where:
V = velocity of the striker at the moment of impact (m/s),
g = local gravitational acceleration (m/s^2), and
h = vertical height of fall of the striker (m).
This assumes no windage or friction.
And the time between the launching striker and strike the specimen is required in analysis setting which calculate by the equation: [7]

$$h(t) = \frac{1}{2}gt^2 + v_\circ t \qquad \text{................ (4)}$$

Where
v_0= is the initial velocity (m/s).
$y(t)$ =is the altitude with respect to time (m).
t= is time elapsed (s).
g = local gravitational acceleration (m/s^2).
With zero initial velocity.

After finishing the applying boundary conditions, solve the model to find the strain energy by the following:

When a material element is loaded by an external agency, part of the supplied energy is dissipated into heat and the remaining part is stored in the material. Damage is caused by the irrecoverable part of the stored energy. Each material has a certain capacity to absorb damage, and failure results as a result of damage accumulation. Because of the difficulty in measuring the heat loss, it is generally assumed that the damage is proportional to the supplied energy, i.e.

$$\Delta W_{damage} \,\alpha\, \Delta W_{supplied}$$

The strain energy may be used as a failure criterion for fiber-reinforced materials. Since this parameter gives equally good results independent of the failure mechanism.[8] The area under the stress-strain graph is the strain energy per unit volume as shown in the following equation as shown in figure (5): [9]

$$\Delta W = \frac{1}{2}\sigma\epsilon \qquad \text{…………..... (5)}$$

Where:

ΔW = Strain energy (Joule/m3).

σ = stress value (MPa).

ϵ = strain value (%).

in the case of impact test can be considered a strain energy formed in the sample equivalent to the absorbed energy by the sample when struck by the striker, and therefore can multiply the amount of strain energy by size of sample for the purpose of obtaining the amount of energy that go into equations (1 and 2) for the purpose of calculating the value of fracture toughness.

Result and Discussion:

A several samples of composite material are tested under impact loading has been considered in the present study with orthotropic material properties as inputs from the theoretical calculation for composite materials mention above.

Figure (6) show the model used in the impact test after a test where the program calculates the stresses and strains which resulting of impact loading and by using the set of equations which mentioned previously, can be calculate the fracture toughness of composite materials.

Table (3) show the summary of theoretical calculations performed to calculate the fracture toughness of the composite materials used in the study.

In these calculations, note increase energy with increasing the number of layers of composite material, this is due to the increase of energy release in the laminates during the impact event and the process that leads to impede the progress of the crack through the composite material and thus to increase the fracture toughness of the material and this corresponds with the findings of the other researchers [10, 11 and 12], from the other hand can be not the strain energy and therefore impact strength for glass reinforced composite higher then carbon reinforced and these due to woven of glass which work on absorbed more energy due to nature of fabric in two directions while the fracture toughness vice versa because the fracture toughness according to it equation dependent on impact strength and modulus of elasticity and the last is very high for carbon reinforced compare to glass reinforced composite.

Figures (7 and 8) shows the relation between theoretical fracture toughness and volume fraction for glass and carbon reinforced respectively., the corresponding fracture toughness plot from the impact simulation show a strong influence of the volume fraction, where the strain energy has the lowest value in composite material which consists of one layer for both types of fibers, this is because no interlaminar failure can occur in this model.

Experiment have been carried out to characterize the candidate composite material under different loading conditions and with various specimen configurations, the analysis of the results and the influence of various parameters on the properties are summarized in the following sections.

Figures (9 and 10) shows the experimental relation between impact fracture toughness and volume fraction of composites used in this study. The maximum fracture toughness is obtained in three layers composite material with sequence (0°/90°/0°), the high modulus of elasticity have a remarkable effect on increasing the fracture toughness, this is in line with the findings of the other researchers [13, 14 and 15].

We also note from Figures above high fracture toughness of composite materials with increased number of layers used in the manufacture of composite material, this is consistent with the findings of the other researchers [14 and 16], exception of the material consists of four layers of carbon fibers where we note that it has the fracture toughness less than the material that consists of three layers of carbon fibers, which may come back as we have to the high modulus of elasticity of the material recent. Perhaps the reason for this is due to the increase in the number of layers in composite material leads to increased resistance material to crack propagation which is blocked transmission the crack through the layers.

If we want to compare the results of the theoretical and practical results, we find that there is a good agreement in impact strength between them and that also it is found that there is not exceed 13% error in estimation of impact strength as shown in the table (5), on the other hand it is found that there is a more difference in the values of fracture toughness between the experimental and simulation, and it was due to the calculations of fracture toughness depends not only on the impact strength but also on the modulus of elasticity of the material, if we take into consideration difference in predicting the modulus of elasticity with the difference in predict impact strength, we find there is more difference in predicting of fracture toughness values. This discrepancy in estimated magnitudes of impact strength attributed to true loading condition and method of composite fabrication, experimental fracture test impact.

Conclusions:

The experimental investigations have shown that, as number of layers and the fibers volume fraction increases, the fracture toughness will also increase but it is not significantly dependent on the fiber orientation. The impact strength of laminates with three layers of carbon fiber is superior as compared to one layers of carbon fiber specimen composite materials, and also the matrix material (Polyphenylene sulfide) features high flexibility and the ability to absorb impact energy, this behaviour is true for all volumes fraction of both types of fibres, number of layers and orientations. It is reasonable to assume that the main energy absorption mechanisms are delamination and deformation including membrane and bending deformations because of fiber breakage.

Table (1) volume fractions and orientation of composite sheet.

No.	Type of fiber	Layers sequences	Volume fraction
1	Glass	1 layer	8
2		2 layers	16
3		3 layers	24
4		4 layers	32
5	Carbon	0°	6
6		0°/90°	12
7		0°/90°/0°	18
8		0°/45°/-45°/90°	24

Table (2) mechanical properties used in numerical simulation.

Material type	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	v_{12}	v_{13}	v_{23}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
1 G	9.3	9.3	3.44	0.342	0.125	0.125	1.34	1. 5	1. 5
2 G	10.9	10.9	3.21	0.334	0.098	0.098	1.47	1.46	1.46
3 G	17.15	17.15	3.01	0.326	0.057	0.057	1.62	1.42	1.42
4 G	18.88	18.88	2.84	0.318	0.05	0.05	1.806	1.35	1.35
0°C	17.27	3.5	3.5	0.347	0.347	0.07	1.318	1.318	1.64
0°/90°C	18.9	18.9	3.31	0.344	0.06	0.06	1.406	1.59	1.59
0°/90°/0°C	33.1	3.14	3.14	0.341	0.341	0.04	1.507	1.507	1.51
0°/45°/-45°/90°C	26.66	26.66	2.99	0.338	0.04	0.04	1.624	1.44	1.44

Table (3), summery of theoretical calculation of impact test.

Material Type	Energy (J)	Impact Strength (kJ/m^2)	Fracture Toughness ($MPa.\sqrt{m}$)
1G	6.65	166.63	39.48
2G	6.77	169.25	42.97
3G	6.74	168.52	53.76
4G	6.81	170.25	56.71
0°C	5.95	148.75	50.7
0°/90°C	6.25	156.26	54.36
0°/90°/0°C	6.43	160.78	72.94
0°/45°/-45°/90°C	6.62	165.5	66.46

Table (4) show the summery of experimental impact resistance test.

Material Type	Absorbed Energy (J)	Impact Strength (kJ/m^2)	Fracture Toughness (MPa.√m)
1G	6.25	156.25	31.72
2G	6.4	160	36.22
3G	6.3	157.5	41.11
4G	6.5	162.5	46.31
0°C	5.4	135	43.19
0°/90°C	5.54	138.5	48.19
0°/90°/0°C	5.78	144.5	62.18
0°/45°/-45°/90°C	6	150	61.73

Table (5). The comparison between theoretical and experimental impact strength.

Material Type	Experi Impact Strength (kJ/m^2)	ANSYS Impact Strength (kJ/m^2)	Percentage error
1G	156.25	166.63	6.64
2G	160	169.25	5.78
3G	157.5	168.52	6.99
4G	162.5	170.25	4.77
0°C	135	148.75	10.18
0°/90°C	138.5	156.26	12.82
0°/90°/0°C	144.5	160.78	11.26
0°/45°/-45°/90°C	150	165.5	10.33

Figure (1) Sheet preparing die

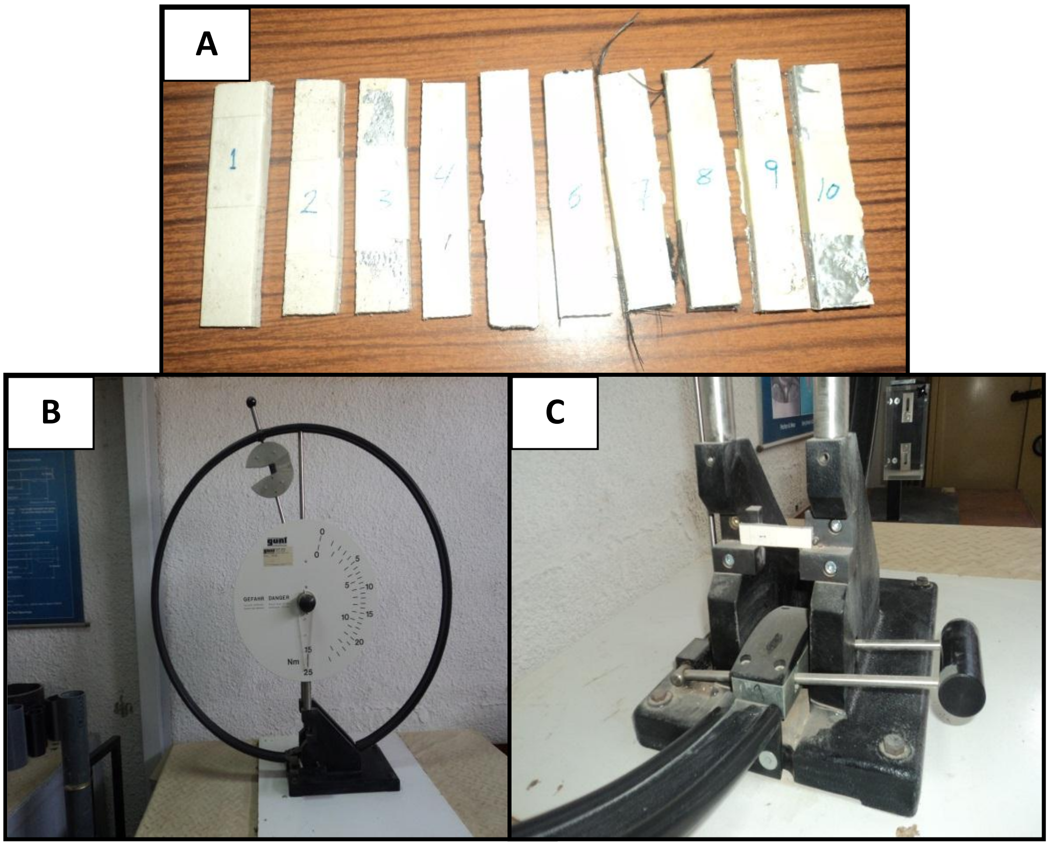

**Figure (2): (a) Experimental impact specimen, (ASTM D256) ,
(b) Impact testing machine and (c) Fixation of specimen.**

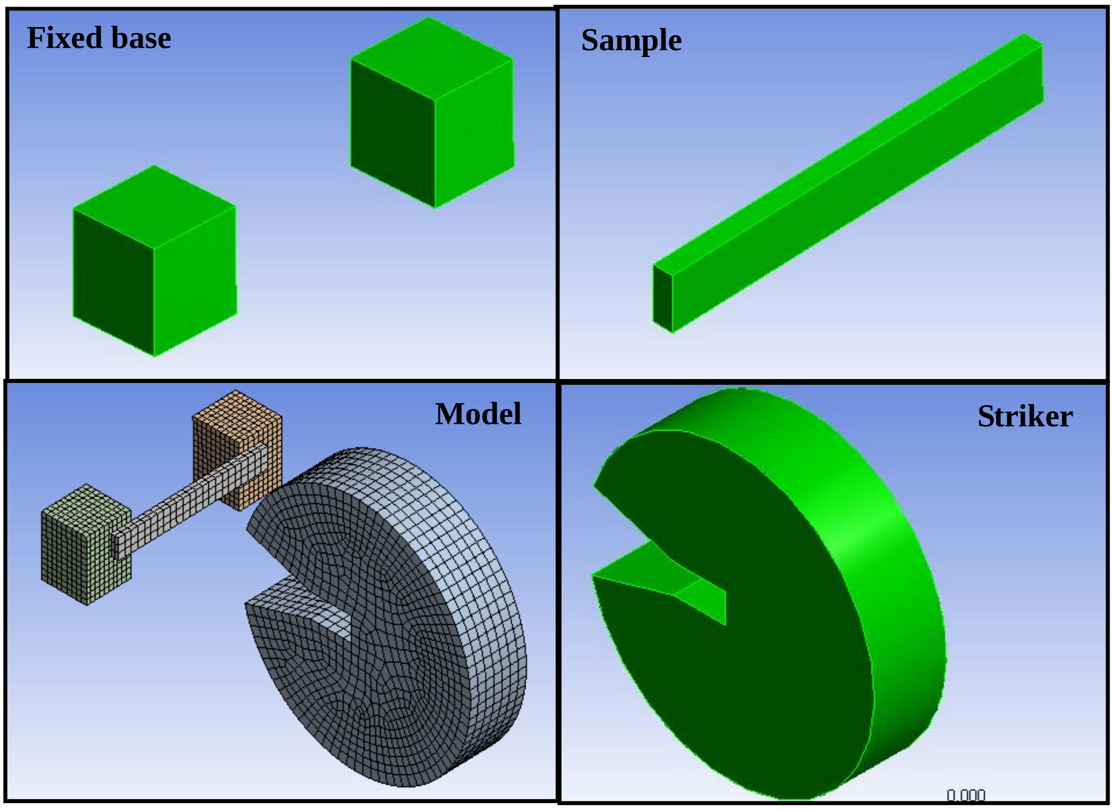

Figure (3): Parts of FE model of impact test

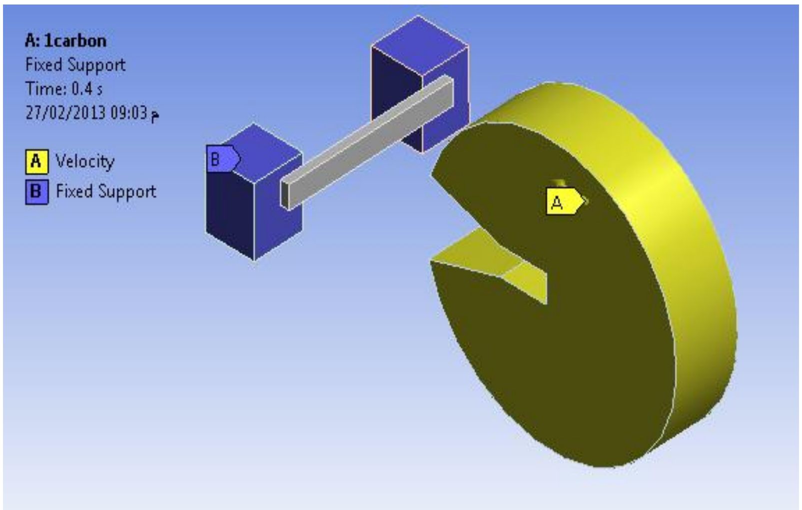

Figure (4) Apply boundary conditions on impact sample.

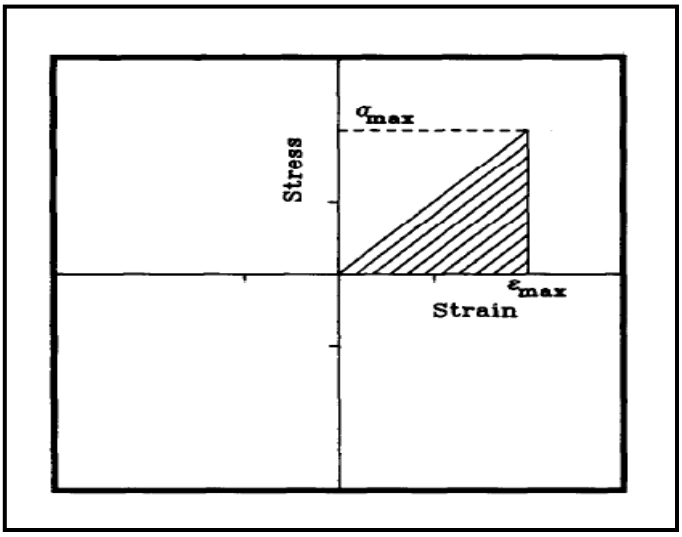

Figure (5) Definition of the strain energy

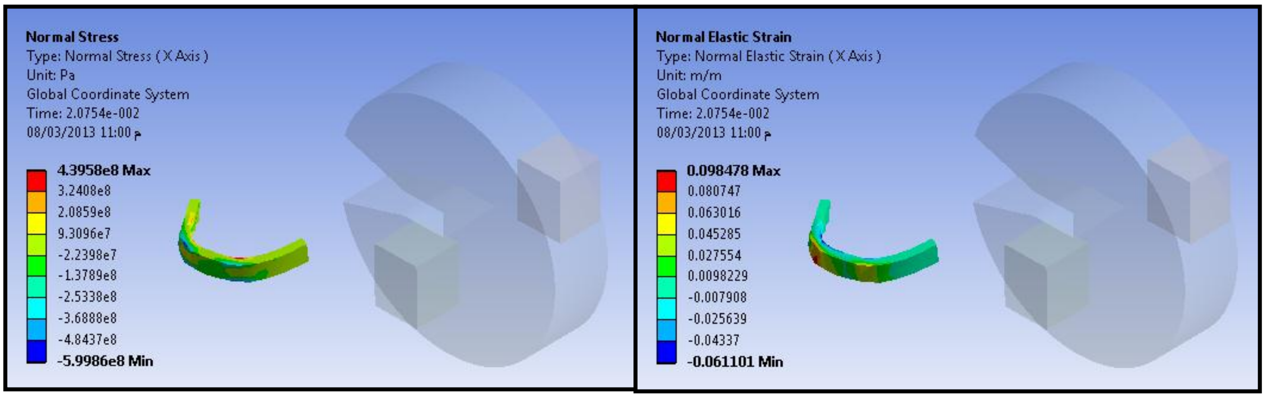

Figure (6): Stress and strain resulting due to impact load.

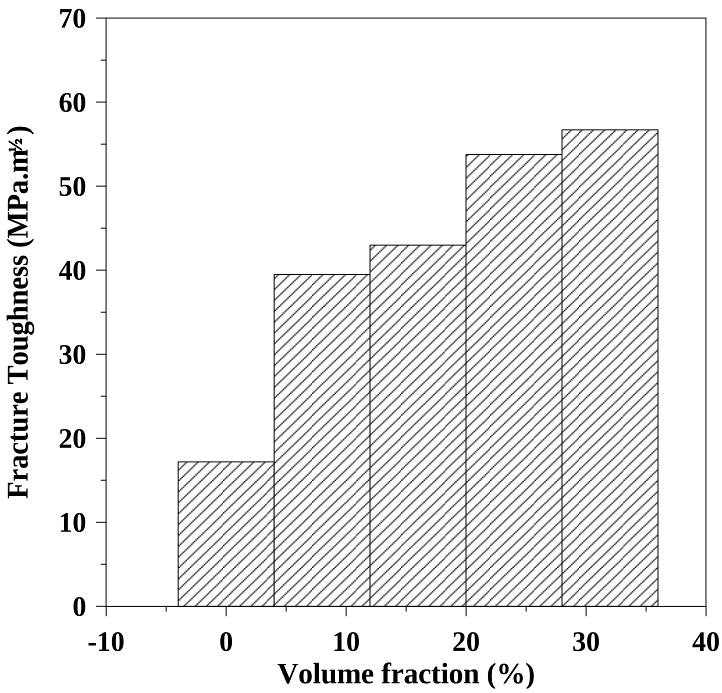

Figure (7), the relation between theoretical fracture toughness and volume fraction for glass reinforced composite materials.

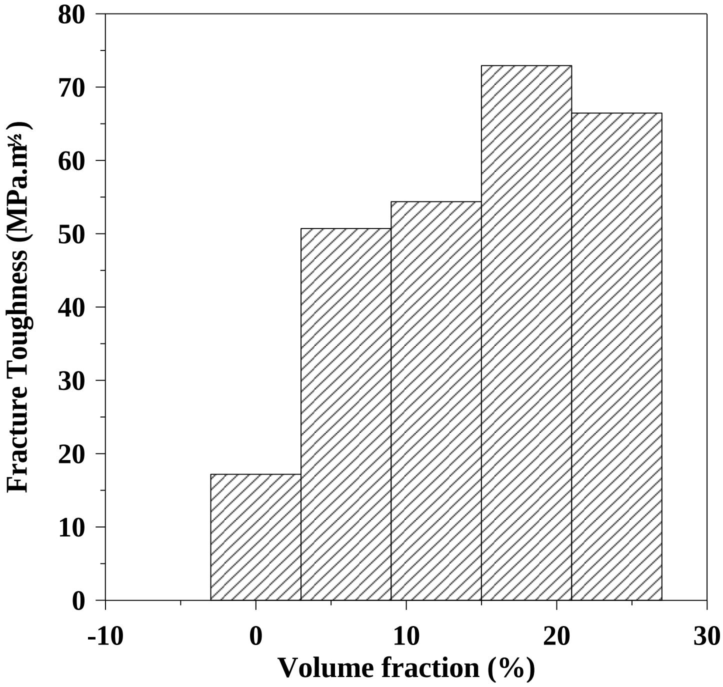

Figure (8), the relation between theoretical fracture toughness and volume fraction for carbon reinforced composite materials.

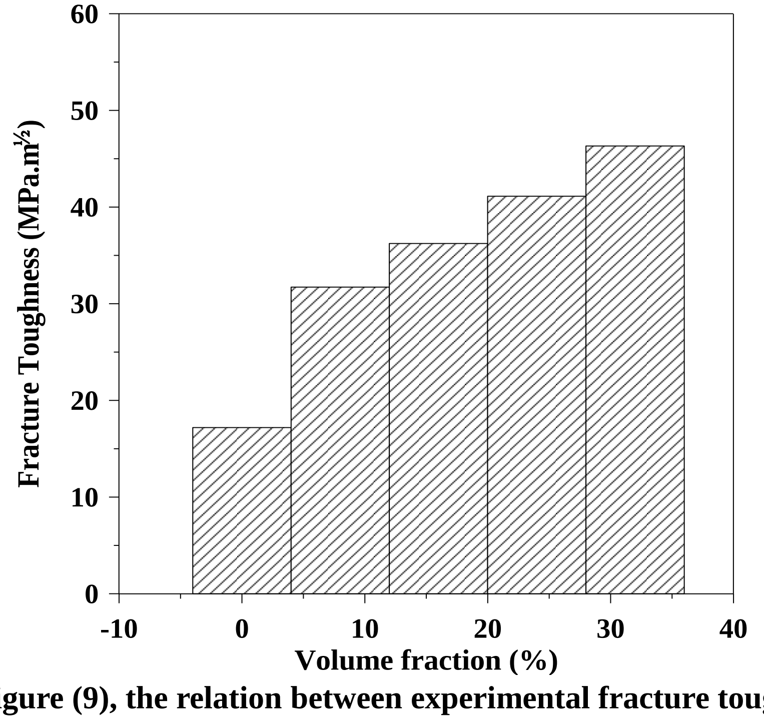

Figure (9), the relation between experimental fracture toughness and volume fraction for glass reinforced composite materials.

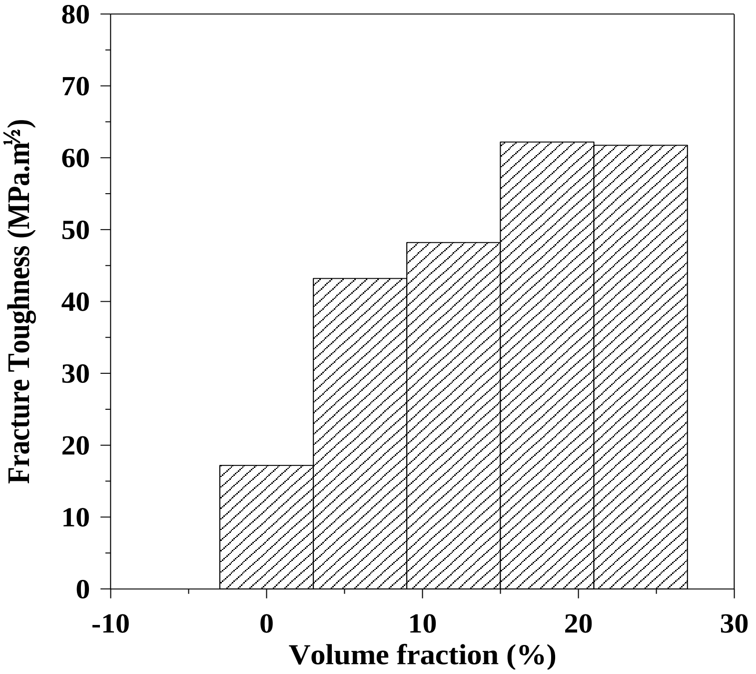

Figure (10), the relation between experimental fracture toughness and volume fraction for carbon reinforced composite materials.

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