GU J Sci, Part A, 8(1): 123-134 (2021)

Gazi University
Journal of Science
PART A: ENGINEERING AND INNOVATION
http://dergipark.gov.tr/gujsa

Araştırma Makalesi Research Article

Failure Analysis of Hybrid Glass Reinforced Composites in Polymeric Industries

Dickson David OLODU[1*]

[1]Department of Mechanical Engineering, Faculty of Engineering, Benson Idahosa University, PMB 1100, Benin City, Edo State, Nigeria

Keywords

Failure Analysis
Fracture Modes
Hybrid Glass Reinforced Composite
Impact Load

Abstract

This research deals with the failure analysis of hybrid glass reinforced composites in polymeric industries. In this research, fourteen specimens with different compositions were developed. The produced test specimens had a dimension of 210mm length, 150mm width and 50mm thickness which were in accordanc--e with American Society for Testing and Materials (ASTM). The fourteen test specimens produced were subjected to impact test. The critical stress, shear stress and stress distribution for mode I and mode II were investigated and results were obtained. The results obtained shows that specimen A had an optimum critical and shear stress of 9.32 MPa and 25.1 MPa for mode I while specimen C had an optimum critical and shear stress of 2.49 MPa and 7.03 MPa for mode II respectively. It was also observed that specimen I which contained 12 plies of soft mat reinforcement required the least stress magnitude to grow the crack, while specimen C which contained 2 plies of woven roving and one ply of hat mat experienced the highest critical stress. Hence, adequate percentage composition of E-glass and polyester reduces failure in hybrid glass composites in polymeric industries.

Cite

Olodu D. D., (2021). Failure Analysis of Hybrid Glass Reinforced Composites in Polymeric Industries. *GU J Sci, Part A, 8*(1), 123-134.

Author ID / (ORCID Number)

Dickson David Olodu, 0000-0003-3383-2543

Article Process

Submission Date	14.11.2020
Revision Date	13.01.2021
Accepted Date	11.03.2021
Published Date	29.03.2021

1. INTRODUCTION

Failure of composite materials when subjected to impact load results to catastrophic failure which poses great challenges in polymeric industries. Mueller & Krobjilowski (2004) examined the fibre-reinforced hybrid composite laminates at different fraction volume of composite materials which involved epoxy resin, plain-woven glass fabric and textile satin fabric. According to Mueller & Krobjilowski (2004), fracture toughness of a material had immense importance in the determination of the resistance of the material to crack propagation. Therefore, in their research, impact behaviour and fracture toughness of the laminates were examined based on American Society for Testing and Materials (ASTM-D256), they analysed the specimen configuration which includes the selection of different notch depths, fibre proportion and orientations. Based on their study, the fracture toughness was found to increase continuously with increased volume of glass fabric and significantly depends on the notch size. The experimental results were validated using analysis of variance (ANOVA) technique, and it was found that the percentage of glass content was approximately 80%, while notch depth and orientation occupied 20% of the composition. Krueger (2006) in his investigation on computational fracture mechanics for composites found that, 'inter-laminar fracture mechanics proved useful for characterising the onset of delamination in composites'. The fracture toughness characterisation and inter-laminar fracture mechanics analysis tools were described demonstratively using applications on the structural level. Dhakal et al., (2006) experimentally investigated

*Corresponding Author E-mail: dolodu@biu.edu.ng

flax, hemp, and kenaf fibres in polypropylene binder for all hybrid fleeces in which the blending ratios were varied from 50/50 to 70/30 natural fibre/polymeric fibre composition. In their study, glass fibre/polypropylene mats were used as reference material. The influence of process temperature on the impact strength and tensile strength of the different composite materials reinforced by natural fibres and glass fibres were determined based on the fibre type. Williams (1978) in his analysis of the fracture mechanics of composites failure reviewed how fracture mechanism can be applied to the various fracture modes observed in composites. It was shown that conventional methods were used for short-fibre composites while the oriented laminates undergo delamination. The importance of delamination toughness in determining composite behaviour was emphasized and details of the various test methods and analysis techniques were given and finally, some discussions of the more complex failures seen in cross-ply laminates were also presented in his study. Pahizgar et al. (1982) applied linear elastic fracture mechanics for the study of orthotropic materials, it was shown that the fracture toughness of unidirectional composites was independent of the crack length but depends on crack-fibre orientation. To verify these claims, glass epoxy material was used. The fracture toughness for different crack-fibre orientations were obtained by utilising Solid Sap Finite Element Program and compact tension specimens. Hence, an empirical formula relating to the fracture toughness of the material for different crack-fibre orientation was found. Olodu & Osarenmwinda (2018) investigated the empirical model of injection moulded high density polyethylene-grass composite. In their study, they concluded that process parameter such as temperature and percentage by volume of the composite material contributes to the strength and failure of composite materials.

This study investigates the failure analysis of hybrid glass reinforced composites in polymeric industries.

2. MATERIALS AND METHODS

2.1. Materials

This research was carried out on samples fabricated by randomly varying plies of reinforcements in form of woven roving, hard and soft E-glass fibre mats, combined in unsaturated polyester resin (specific gravity 1.12, viscosity of 65cps and gel time of 25 min) matrix. The catalyst and accelerator used were methyl ethyl ketone peroxide (MEKP) and cobalt respectively due to their compatibility in polyester as curing agents at ambient temperature condition.

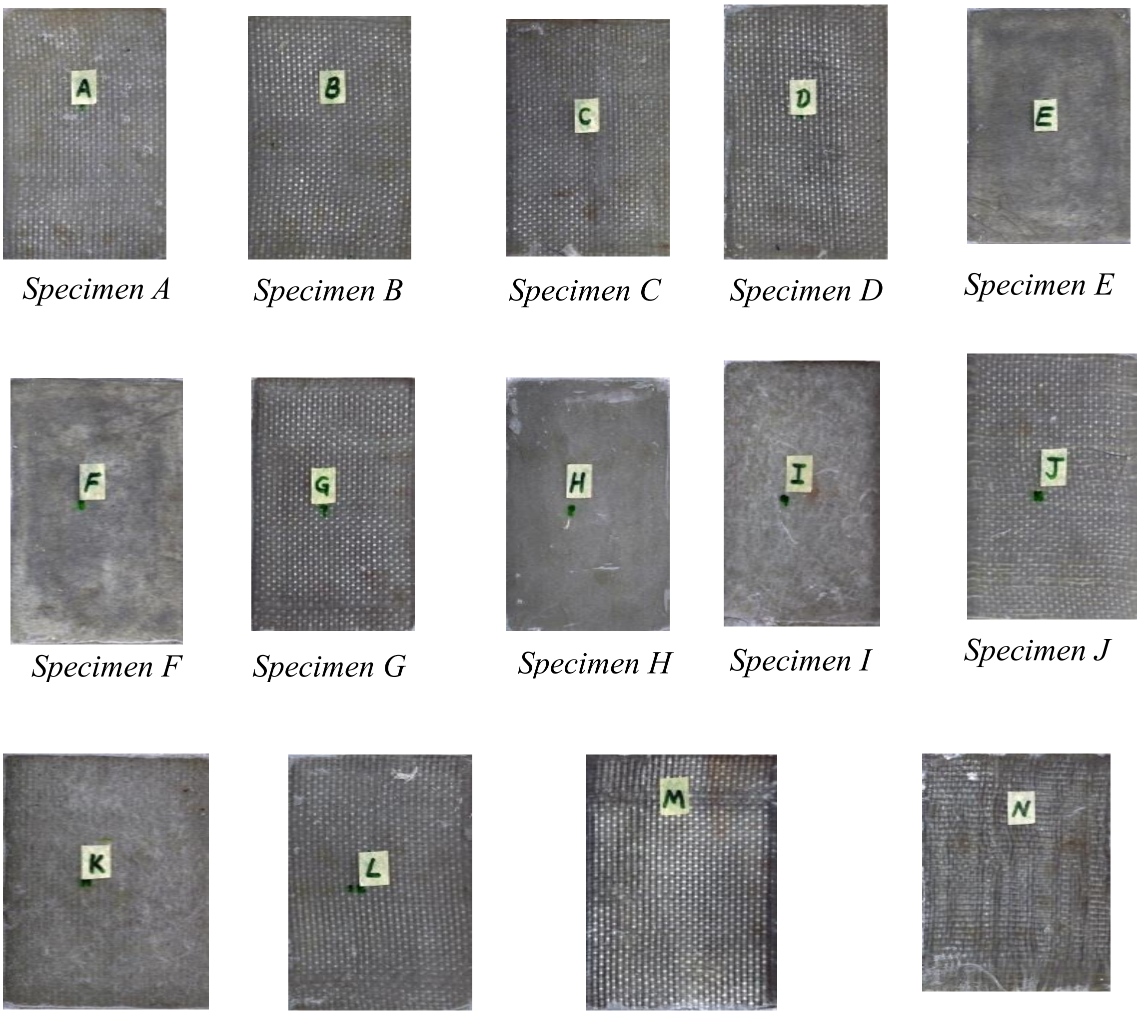
2.2. Reinforced Composite Specimen Manufacture and Preparation

The hand lay-up method was used for the production of 14 samples which consist of the randomly varied E-glass fibre reinforcement plies, neatly laid in an already prepared mould measuring *210 mm x 150 mm x 50 mm*. Hence, the reinforcement was impregnated with catalysed polyester resin, and allowed for a period of one month to completely cure at ambient condition. These tests samples were cut into 28 specimens, 14 of these samples were compact tension (CT) specimens used for fracture mechanics test and the other 14 specimens were for impact tests respectively. The developed test specimens were cut using the hack saw in accordance with the ASTM and ISO standard for fracture mechanics and impact tests respectively for composite materials (Figure 1).

2.3. Fracture Mechanics Assumptions in Reinforced Composite Analysis

The following assumptions were made in this study:

i. Resin interlayer is isotropic and has uniform thickness.
ii. The plies or layers are perfectly bonded in the laminate everywhere except in the region where a flaw is initiated or present from the surface notched tip.
iii. There is perfect bonding between the resin and the fibre.
iv. The resin and the fibres are experiencing the same stress due to the applied impact force.
v. Crack tip have zero radius.



Specimen A *Specimen B* *Specimen C* *Specimen D* *Specimen E*

Specimen F *Specimen G* *Specimen H* *Specimen I* *Specimen J*

Specimen K *Specimen L* *Specimen M* *Specimen N*

Figure 1. *Samples of Reinforced Polyester Composite Plates Manufactured*

2.4. Linear Elastic Fracture Mechanics

In the analysis of the fracture mechanics of reinforced polyester composite, the Linear Elastic Fracture Mechanics (LEFM) which according to Williams (1978), was used to analysed elastic stresses in the neighbourhood of pre-existent cracks of specified intensity, for which its purpose is to ascertain the level of applied stress, σ, at which pre-existent cracks of various sizes and geometries will propagate; and impact test approaches were used, where emphasis is focused on exploring the fracture mechanics at the crack tip of the fibre reinforced composite when subjected to impact force. The test was conducted under plane stress condition.

According to Pahizgar et al. (1982) the proper way to begin a study of fracture in orthotropic materials (reinforced composite material) is to compare their fracture with the fracture of isotropic materials and then model the fracture mechanism as homogeneous anisotropic materials. Based on the principle of LEFM, the following can be stated that:

a) The crack will advance along the original crack direction.
b) The crack tip displacements can be separated into three different modes: crack-opening mode (Mode I); edge or in-plane sliding mode (Mode II); and crack tearing or out-plane mode (Mode III).
c) The crack tip stress and displacement equation for the above modes are given by Westergaard's equations (Equation 2).

2.5. Test Procedures for The Determination of Mode I Stress Intensity Factor, K_I

Before the determination of K_I, the CT specimen composition was manufactured as shown in Figure 2. The CT specimens were drilled to make provision for the pins through which loads were introduced on the test specimens using a U-bracket which is attached to the Universal Testing Mechanic. The loading brackets were properly aligned with the specimen to avoid twisting while the crack propagation takes place (Figure 3).

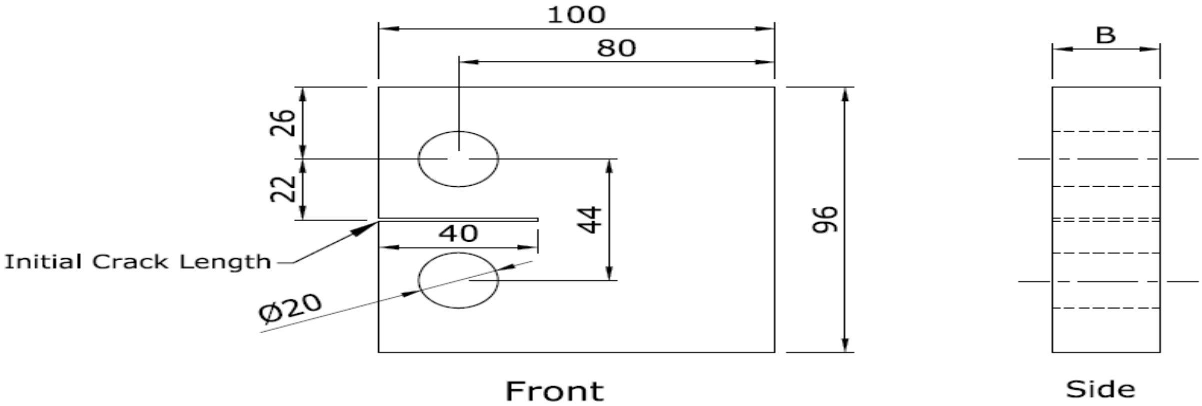


Figure 2. *ASTM Standard Pre-Cracked Compact Tension (CT) Specimen*

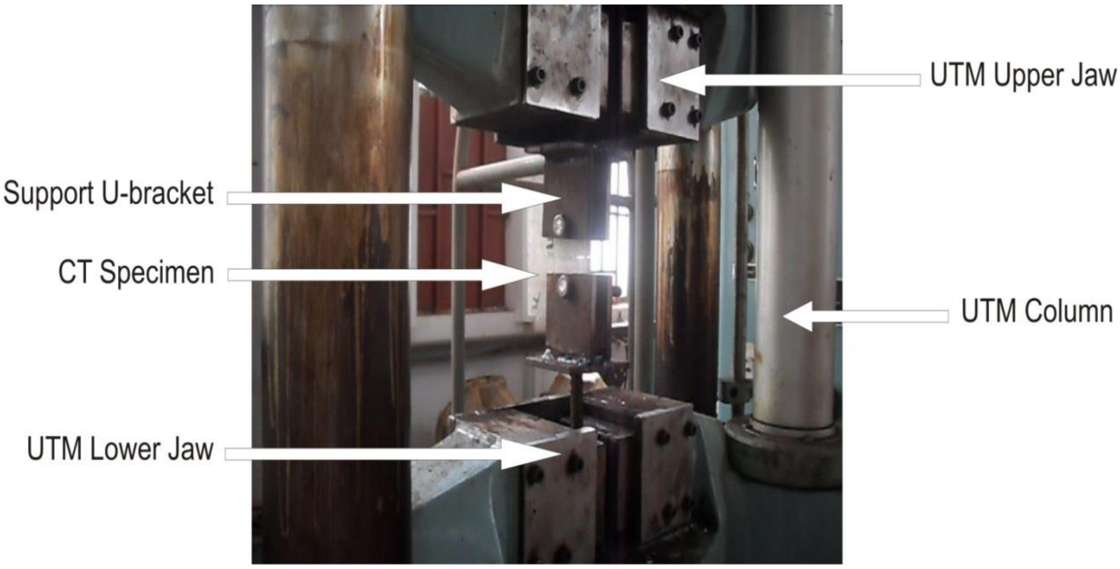


Figure 3. *Fracture Test of CT Specimen on the UTM*

2.6. The Test Machine Used for The Fracture Test

The test machine used for the fracture test was capable of being operated in displacement controlled mode with constant displacement rates in range of 0.55mm per minute. The load sensing device had accuracy over a load range of within ±1% of the indicated value. The crosshead separation was used to measure the CTOD of the specimen through the loading brackets attached. As the opening displacement increased, the crack growth front advancement along the ligament was marked on the specimen. The load, displacement and crack growth length along the ligament were continuously monitored, measured and recorded till the CT specimen could no longer sustain the loading and thus fractured. During the test, two replicate tests were done for every specimen containing an initial crack of length, 40mm which is $0.25W$ produced on the specimens. The advantage is to force the crack initiated to propagate along a straight line to comply with the Linear Elastic Fracture Mechanics (LEFM) requirements. Another purpose of notching and pre-cracking the test specimen is to simulate an ideal plane crack with essentially zero tip radius which agreed with the assumptions made in stress intensity analyses. Each specimen test record consisted of a plot of the output of a load versus the displacement and the crack length extension measurement. The conventional plot of load along the *y*-axis and the displacement along the *x*-axis was maintained.

2.7 Analysis of Load-Displacement Records and Calculation of K_I

The failure analysis of hybrid glass reinforced composite in polymeric industries were carried out using Equation 1 to 4. The ASTM standards for the mode I stress intensity factor (SIF), K_I calibration for the CT specimen is given by Equation 1;

$$K_I = \frac{P}{BW^{1/2}} f\left(a_i/W\right) \tag{1}$$

Where P = maximum load

The expression for K_I determination is accurate to within 0.5%, over the entire range of a/W $\left(a/W < 1\right)$ as presented in Janssen et al. (2004). The mode II stress intensity factor was obtained using Equation 2;

$$K_{II} = \tau_{n\theta}\sqrt{\pi a} \tag{2}$$

Hence, for a crack length of *a*, the critical stress, σ_C were determined according to the stress intensity factor criterion using Equation 3;

$$\sigma_C = \frac{K_{IC}}{\sqrt{\pi\left(a+\ell\right)}} \tag{3}$$

Where, ℓ = The damage zone at each crack tip which was determined from the experiment during failure along the crack ligament (Idicula et al., 2009).

2.8 Experimental Procedure for Impact Strength Determination

The specimens were cut, after which, the specimen was position in the anvil. The proper position of the impact head (striking edge) and the height of the pendulum were set. After securing the specimen, the pendulum was raised to position and allowed to freely swing towards the specimen to impact it to breaking, because the test was a destructive test similar to the fracture mechanics test (Figure 4).

The energy required to break the specimen was determined from the data recorded on the metering device on the machine. According to Radif & Ali (2001), one method of expressing the impact energy for a composite material by adopting a fracture mechanics approach is in terms of the relation (Equation 4);

$$U = \frac{E}{\phi b\left(d-c\right)} \tag{4}$$

Where U = Impact energy; E = Energy in KJ/m^2 which is registered for the test specimen; b = breadth; d = depth; c = notch; ϕ = a calibration factor which depends on specimen and crack dimension and compliance (Osarenmwinda & Nwachukwu, 2010; Orbulov & Ginsztler, 2014; Romanova et al., 2009).

Figure 4. *Charpy Impact Test Machine*

3. RESULTS AND DISCUSSION

Table 1shows the mode I stress ıntensity factor and critical stress for all 14 specimens while Table 2 shows the mode II stress ıntensity factor and shear stress for all 14 specimens. Furthermore, Figure 5 shows a quadratic relation of mode-I stress ıntensity factor curve at different critical stress level for all specimens; Figure 6 shows the linear relation of mode-II stress ıntensity factor at different shear stress level for all specimens; Figure 7 shows the stress distribution around locations ahead of crack for all specimens; Figure 8 shows the fractured compact test specimen after test while Figure 9 shows the ımpact energy versus ımpact strength curve. Table 1 shows the mode-I stress ıntensity factor and critical stress for all 14 specimens while Table 2 shows the mode ıı stress ıntensity factor and shear stress for all 14 specimens

Table 1. *Mode I Stress Intensity Factor and Critical Stress for All 14 Specimens*

Laminate Specimens	**Stress Intensity Factor, K_I (MPa.m$^{1/2}$)**	**Critical Stress, σ_c (MPa)**
A	9.32	25.1
B	6.57	18.31
C	9.49	25.82
D	6.41	17.44
E	6.59	18.36
F	6.59	18.36
G	6.65	18.2
H	4.47	12.19
I	3.02	8.36
J	4.87	13.57
K	4.68	12.88
L	6.17	16.88
M	6.7	18.23
N	4.86	13.22

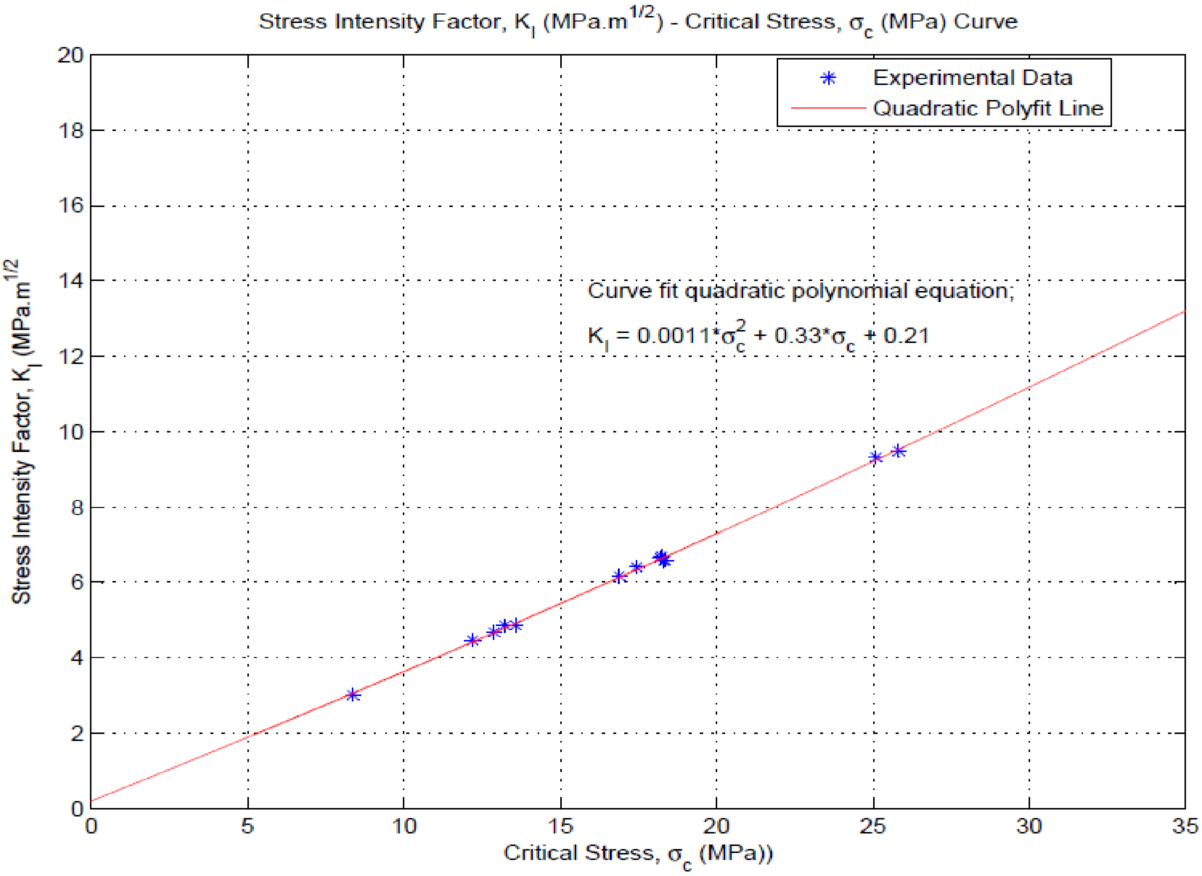


Figure 5. *Quadratic Relation of Mode-I Stress Intensity Factor Curve at Different Critical Stress Level for All Specimens*

Table 2. *Mode II Stress Intensity Factor and Shear Stress for All 14 Specimens*

Laminate Specimens	**Stress Intensity Factor, K_{II} (MPa.m$^{1/2}$)**	**Shear Stress, $\tau_{n\theta}$ (MPa)**
A	2.42	6.84
B	1.77	5.00
C	2.49	7.03
D	1.68	4.74
E	1.83	5.15
F	1.78	5.01
G	1.75	4.95
H	1.18	3.32
I	0.81	2.28
J	1.31	3.70
K	1.25	3.53
L	1.63	4.59
M	1.75	4.94
N	1.28	3.60

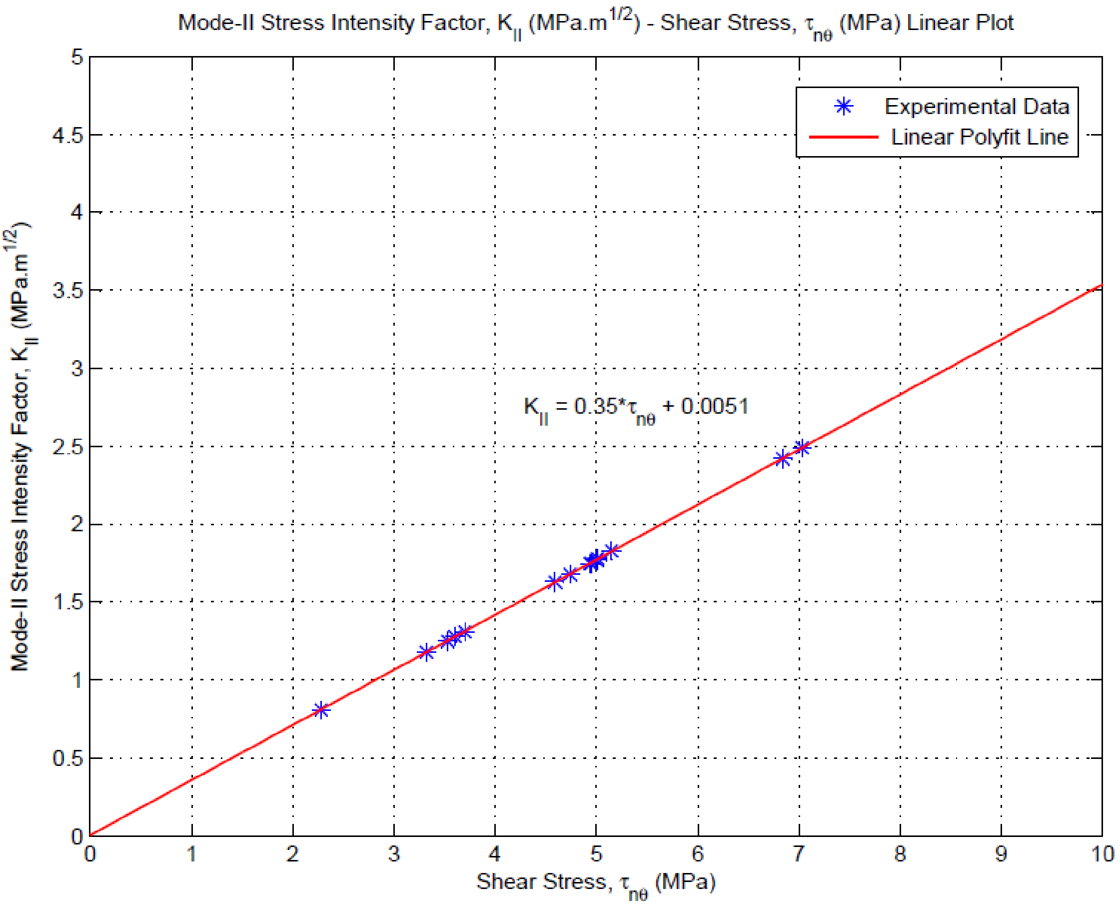


Figure 6. *Linear relation of Mode-II Stress Intensity Factor,* K_{II} *Curve at Different Shear Stress Level for All Specimens*

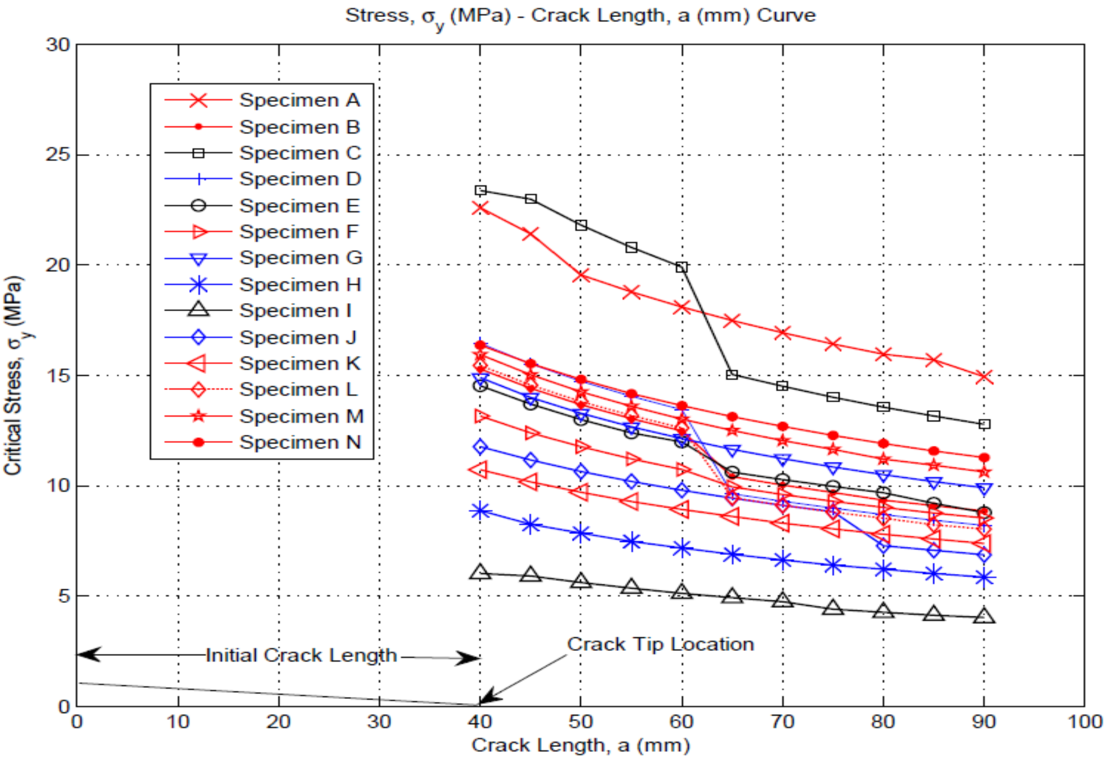
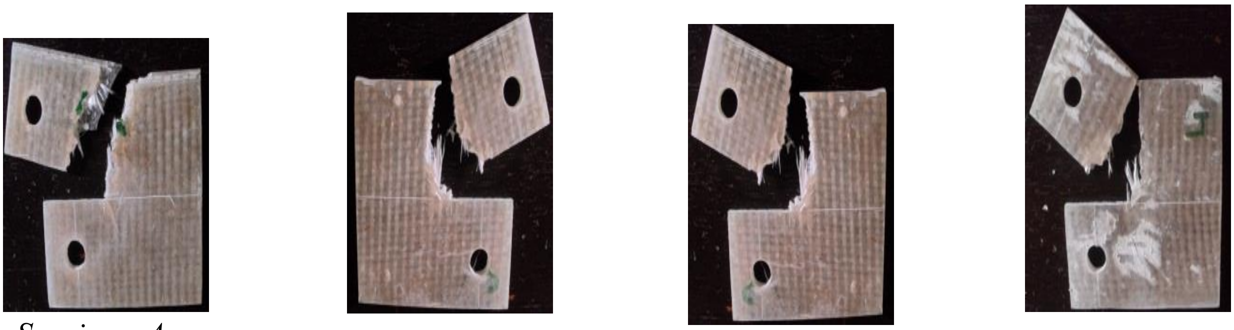
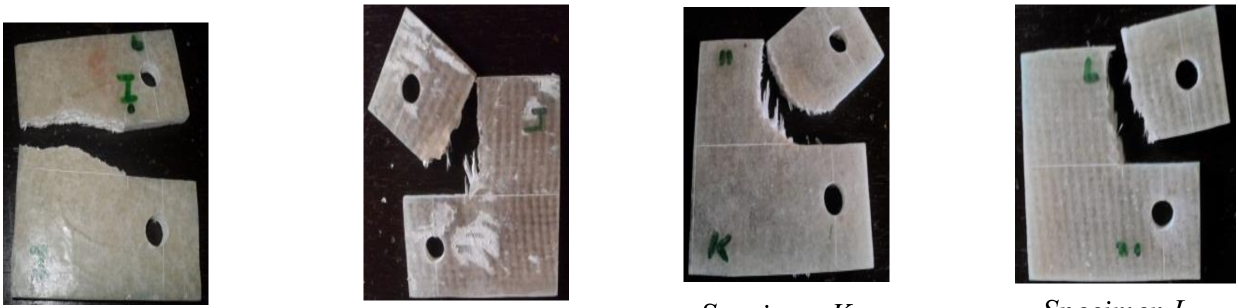


Figure 7. *Stress Distribution Around Locations Ahead of Crack, a (mm) For All Specimens*

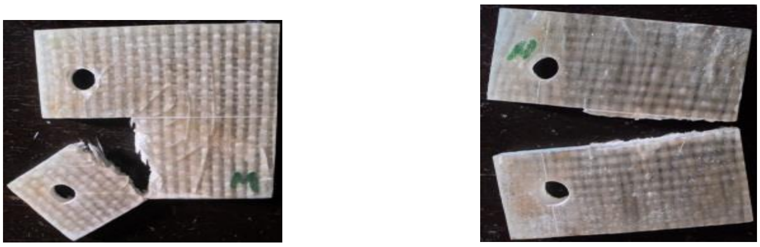


Specimen A *Specimen B* *Specimen C* *Specimen D*

Specimen E *Specimen F* *Specimen G* *Specimen H*



Specimen I *Specimen J* *Specimen K* *Specimen L*



Specimen M *Specimen N*

Figure 8. *Fractured CT Test Specimen After Test*

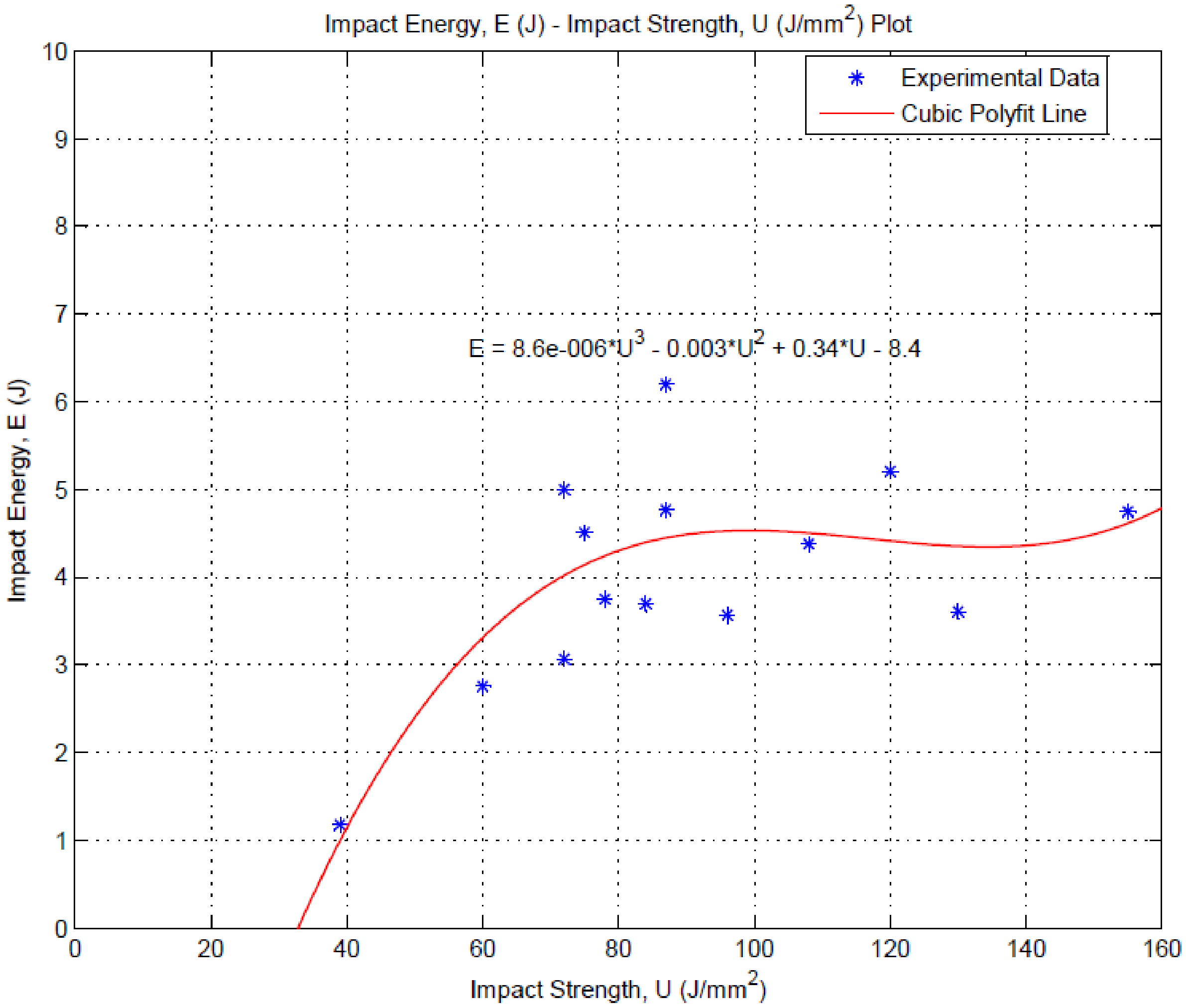


Figure 9. *Impact Energy versus Impact Strength Curve*

3.1. Discussion of Results

3.1.1. Stress Intensity Factor, K_I and Critical Stress, σ_c Data Analysis

A factor that was found to be a major influence on the decreasing magnitude of K_I and K_{II} was the increase in thickness of the specimens. This mean that the larger the thickness, the higher the volume of materials being subjected to the maximum stress along the point geometric discontinuity with a greater probability of finding a weaken region that cannot resist the maximum stress which will assist the crack growth. This is because; the size effect is related to the increased amount of surface area where cracks initiates. The observed increase of the stress intensity factor, K_I and K_{II} with respect to the critical stress, σ_c as shown in the Figure 5 and 6, having a linear relationship can related to the above condition, of maximum stress being present at the point of geometric discontinuity in the neighbourhood of a flaw before degenerating into macroscopic crack. As the stress progressively increases, the crack continues to open and grow with ease, which sufficed that the principle of linear elastic fracture mechanics was upheld as indicated by Griffith criterion for the propagation of crack in that it states that; a crack will continue to propagate when the decrease in elastic strain energy is at least equal to the energy required to create the new crack surface (Mueller & Krobjilowski, 2004).

3.1.2. Critical Stress Distribution at Different Crack Length

Using Equation 3 to model the stress distribution near the crack tip, it could be shown that the region around the neighbourhood of the crack tip experienced higher stress state than other regions not around this vicinity. This was expressed in the stress distribution versus crack length curve as shown in Figure 7. Taking a look at the fracture mode of the CT specimens under mode I loading condition, it was observed that fracture of specimens containing woven roving, namely; specimen A, B, C, D, G, J, K and M with the exception of specimen N, was not all along or in the direction of the original crack. The crack was observed to change direction as it propagates at an angle that was almost at 90° to the horizontal, without any crack growth in the initial crack direction, although this was not the case for all of them as some were seen to grow in the initial crack direction before change direction. The change in crack growth direction was a resistance posed by crack arrest from fibre bridging. This was also observed from the curves to result a decreased in the stress at the location. This could be explained as a change in direction as the crack grows will require a reduced stress level to grow the crack in that direction as the stress intensity at these locations are excessively higher. But for specimens E, F, H, I with the exception of specimen N contained soft and hard mat reinforcements. The cracks were observed to grow along the initial crack direction as a result of the reinforcement composition as this followed the LEFM principle. This could be raced to the form and mechanical properties of the fibre used which could not resist the crack growth efficiently. This shows that composites containing woven roving reinforcement were better fracture resistant composite material than soft and hard reinforcement mats. The weaving pattern of the woven roving was a key factor which contributed to its distinguished performance. From Figure 7, it be shown that specimen I which contained 12 plies of soft mat reinforcement required the least stress magnitude to grow the crack, while specimen C which contained 2 plies of woven roving and one ply of hat mat experienced the highest critical stress.

3.1.3. Failure Analysis of Hybrid Glass Reinforced Composites

Failure analysis was carried out by analysing the appearance of the fractured specimens and review of the slow video motion pictures and the photographs taken of the some samples selected. Figure 8 shows the appearance of fractured surface of specimens subjected to impact, two types of fractures were observed. In the first case laminate failed completely into two pieces, the fibres on the fractured surface were straight indicating minimal fibre pull-outs, and such failure were observed to occur in the case of laminates plies of either soft or hard mats reinforcements. The second type of failure was observed in specimens containing woven roving mats, used as reinforcement or had greater volume fraction of fibre. The fracture surface was characterised by fibre pull-outs and this was an indication that there was resistance from the fibre under the sudden impact force. The fracture appearance was same for all the laminates containing woven roving irrespective of percentage of glass content of either soft or hard mat. Figure 9 indicated an increase in impact strength as the impact energy absorbed by the specimen increased. This shows that the energy absorption capacity of a composite material is dependent on the fibre volume which in turn affects the thickness.

4. CONCLUSION

The research on the failure analysis of hybrid glass reinforced composite in polymeric industries had been achieved. It was observed from the experimental results that woven roving has been seen to posses exceeding resilience and resistance during sudden impact force compared to soft and hard mat reinforcement. It was also observed from the stress intensity and critical stress versus crack length curve, that the crack tip is where the maximum stress exists . It is also the location of the minimum stress intensity factor. This is an indication that glass reinforced polyester composites has the tendencies to resist damage and crack propagation when exposed to sudden impact force, if the internal structure and surface are void of defects and microcracks resulting from blisters, foreign particle, holes and fibre-matrix debonds, that is, the energy required to grow the crack will be inactivated or equal to zero. The mode I fracture toughness, K_{IC} was found to have a value of 2.5 MPa while the mode II fracture toughness, K_{IIC} was 1.3 MPa.

CONFLICT OF INTEREST

There is no conflict of interest in this research article.

REFERENCES

Dhakal, H. N., Zhang, Z. Y., Richardson, M. O. W., & Errajhi, O. A. Z. (2006). The Low Velocity Impact Response of Non-woven Hemp Fibre Reinforced Unsaturated Polyester Composites. Advanced Polymer and Composites (APC) Research Group, Department of Mechanical and Design Engineering, University of Portsmouth. Retrieved from www.elsevier.com.

Idicula, M., Joseph, K., & Thomas, S. (2009). Mechanical Performance of Short Banana/Sisal Hybrid Fibre Polyester Composite. *Journal of Reinforced Plastics and Composites, 29*(1), 12– 29.

Janssen, M., Zuidema, J., & Wanhill, R. J. H. (2004). Fracture Mechanics. (2nd Edition). New York: Spon Press.

Krueger, R. (2006). Fracture Mechanics for Composites: State-Of-The-Art and Its Challenges. NAFEMS Nordic Seminar: Prediction and Modelling of Failure Using FEA, National Institute of Aerospace, USA. Retrieved from ntrs.nasa.gov

Mueller, D. H., & Krobjilowski, A. (2004). Improving the Impact Strength of Natural Fibre Reinforced Composites By Specifically Designed Materials and Process Parameter. *International Nonwovens Journal, 13*(4), 31-38.

Olodu, D. D., & Osarenmwinda, J. O. (2018). Emperical Modelling of Injection Moulded High Density Polyethylene-Grass Composite. *American Journal of Engineering Research (AJER)*, *7*(12), 245-250.

Orbulov, I. N., & Ginsztler, J. (2014). Compressive Behaviour of Metal Matrix Syntactic Foams. *Acta Polytechnica Hungarica*, *9*(2), 43-56.

Osarenmwinda, J. O., & Nwachukwu, J. C. (2010). Development of Composite Material from Agricultural Waste. *International Journal of Engineering Research in Africa, 3*, 42-48.

Parhizgar, S., Zachary, L. W., & Sun, C. T. (1982). Application of the Principle of Linear Fracture Mechanics to the Composite Materials. *International Journal of Fracture Mechanics, 20*, 3-15.

Radif, Z. S., & Ali, A. (2001). Fracture Toughness of Kenaf Mat Reinforced Polyester Composite. *Pertanika Journal of Science and Technology*, *99*(1), 177-187.

Romanova, V. A., Balokhonov, R. R., & Schmauder, S. (2009). The Influence of the Reinforcing Particle Shape and Interface Strength on the Fracture Behavior of a Metal Matrix Composite. *Acta Materialia, 57*(1), 97-107.

Williams, J. G, (1978). Linear Fracture Mechanics. *Advances in Polymer Science*, *27*, 69-82.