Investigation Of The Stress Intensity Factors Of A Reinforced Polymeric Composite At Different Fracture Modes

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Abstract: Reinforced polyester composites potentials cannot be fully harnessed and exploited unless their fracture modes and failure mechanisms under impact force are fully understood, and appropriate design tools for failure prediction are developed and validated. This study therefore, investigate the stress intensity factors of a reinforced polymeric composite (reinforced polyester composite) at different fracture modes. In this study, the polyesters were reinforced with E-glass fibre in forms of woven roving with either hard or soft mat. Fourteen (14) test samples with dimension 210mm by 150mm were developed, cut and tested in accordance with America Standard of Testing Machine (ASTM) for polymeric composites under Mode I, Mode II and Charpy impact test conditions respectively. Destructive test method was used as the process was observed and studied under a video motion camera, making it possible to monitor the damage as it progressed; crack propagation and final fracture of the specimen on a macroscopic scale level were taken. From the experiment, it could be established that the stress intensity factor is a function of the presence of a crack on the composite structure, the magnitude of the load, and the thickness of the specimens. These factors influence the rate of crack propagation in the test specimens. Specimen I was found to have the smallest stress intensity factor with a thickness of 10.3mm at maximum load of 0.91kN. This could be traced to the form and volume fraction of reinforcement. Furthermore, specimen C was observed to possess the highest optimal stress intensity factor of 9.49 MPa.m$^{1/2}$ and 2.49 MPa.m$^{1/2}$ at critical stress of 25.82MPa and 7.12MPa for mode-I and mode-II respectively. Therefore, specimen C had the highest tendency for crack to propagate due to excessive build-up of stress around the crack tip at every stage, as this could be traced to the composition of reinforcement.

Keywords: Fracture Modes, Reinforced Polyester Composite, Specimens, Stress Intensity Factors.

1. Introduction

In the analysis of impact damage and fracture of composites, the review of the sources, nature and curvature of impactor and how these fracture initiation takes place, propagate from a micro-structural scale at the sites of flaws, and how the coalescence of these flaws leads to a visible separation process that manifests on a macro-structural level before resulting in a catastrophic failure are vital.

From Làszló and George [1], the mechanical and thermal behaviours of a structure depend on the properties of the fibres and the matrix and on the amount and orientations of the fibres. In the structural analysis of composites, the design steps from the micromechanics (which takes into account the fibre and matrix properties) through macro-mechanics (which treats the properties of the composite) are taken into consideration. The fracture behaviour of reinforced composite structures represents the most critical issues in the automotive and aerospace engine fields. Radif and Ali [2] in their studies of the fracture toughness of kenaf mat reinforced polyester composite estimated and analysed the crack criteria by using the mathematical laws that were limited to E1820 standard and the results affirmed by applying the numerical solution of ANSYS to estimate the fracture toughness value K_{IC}, besides the energy release rate of biomass composite. The fracture characterisation of the composites was carried out using the compact tension (CT) specimen that was common used to determine the mode-I fracture properties. The fracture toughness was found to be independent of pre-crack length while the tests were performed at room temperature. It was found that the numerical simulations of the ANSYS model result demonstrated a good agreement between the experiments computed results of the fracture toughness [2]. According to Mueller and Krobjilowski [3], fracture toughness of a material had immense importance in the determination of the resistance of the material to crack propagation. Hence in their research, impact behaviour and fracture toughness of the laminates were examined based on America Standard of Testing Materials (ASTM-D256), they analysed the specimen configuration which included 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. Thus, the fracture propagation was found to be dependent on the fibre percentage of the composite. Szekrényes [4] in an overview on the experimental investigations of the fracture toughness in composite materials, several experimental measures of determining the fracture properties of reinforced composites were shown. The aim of the research was to summarize publications about different experimental investigations of the fracture properties of composites materials. From his study, it was observed that fracture and damage in composites could be influenced by many parameters. Williams [5] 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. Mandel et al. [6] “studied the micromechanical growth of crack in fibre reinforced materials using a 2-D, micromechanical finite element study of stress conditions near crack the tip. The mechanical properties, interface between the fibres and matrix material and the geometry were considered. A close agreement between finite element and experimental values for the loading required for both the initiation of crack growth in the material and arrest by the fibres showed that micromechanical finite element studies are applicable for the development of engineering models for the fracture toughness of fibre reinforced material. It was also shown that the presence of high modulus fibres could significantly reduce the opening mode (mode-I) stresses in the matrix material near the crack tip and could result in crack arrest and an increase in the effective fracture toughness. Furthermore, it was noted that the shear stresses in the matrix material adjacent to the fibre and bond stresses between the fibre and matrix material are larger for a shear mode loading than for an opening mode loading. Although the stresses do not directly result crack growth, they were observed to cause fibre delamination which in turn could result in unstable crack growth”.

This study investigates the stress intensity factors of a reinforced polymeric composite (reinforced polyester composite) at different fracture modes.

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 Fracture Mechanics Assumptions in Reinforced Polyester Composites 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.

2.3 Linear Elastic Fracture Mechanics (LEFM)

Pahizgar et al.,[7] studied the fracture in orthotropic materials (reinforced composite material) and compared the results with the fracture in isotropic materials They concluded by modelling 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) as shown in figure 1.

c) The crack tip stress and displacement equation for the above modes are given by Westergaard’s equations [1].

2.4 Failure Criteria of Composite Materials

Figure 1 illustrates the crack propagation. The following failure criteria were observed in this study:

a) Crack Opening mode I: The crack surfaces separate symmetrically with respect to the planes xy and xz.
b) In-plane Sliding mode II: The crack surfaces slide relative to each other symmetrically with respect to the plane xy and skew-symmetrically with respect to the plane xz.

c) Tearing mode III: The crack surfaces slide relative to each other skew symmetrically with respect to both planes xy and xz.

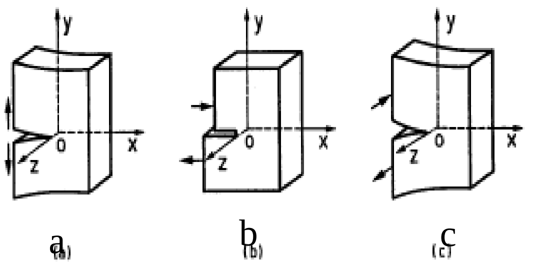

Figure 1: *The three basic modes of crack extension*

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

Before the determination of K_I, the compact tension specimen, various specimens of different compositions were manufactured; the manufactured specimens were marked out as shown in Figure 2 below. Hence, the compact tension specimen was drilled to make provision for the pins through which the load was introduced on the specimen, using a U-bracket which is attached to the Universal Testing Mechanic.

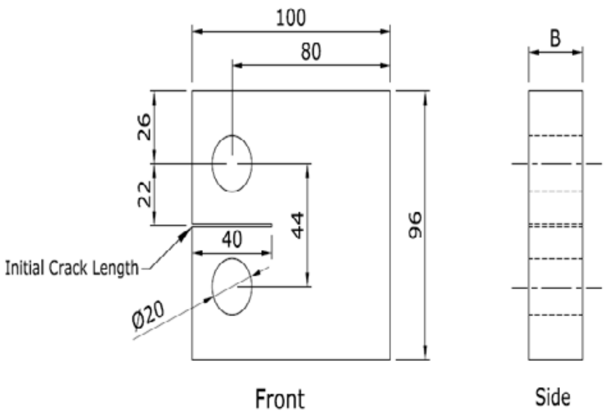

Figure 2: *ASTM standard pre-cracked Compact Tension (CT) specimen.*

2.6 Analysis of Load-Displacement Records and Calculation of K_I

The test will not be valid if $P_{\max}/P_Q > 1.10$, where P_{max} is the maximum load the specimen was able to sustain. In the geometrical construction, the 5 per cent secant offset line represents the change in compliance due to crack growth which is equal to 2 per cent of the initial length [8]. When maximum load P was determined, the value of K_I could be calculated using the stress intensity factor expression for the compact tension specimen as recommended by ASTM [9]. The ASTM standards for the mode I stress intensity factor (SIF), K_I calibration for the compact tension (CT) specimen is given by;

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

The stress intensity factor as very important property in fracture criteria which depends on the applied load and the material configuration shall be computed for the mode II loading using the expression [10[;

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

where $\tau_{n\theta}$ is the shear stress parallel to the crack shall be determined using the stress transformation by method of equation [11]. From the wedge method of stress transformation, we have that; the force in the *y* direction is given by;

$$P = -\left(\sigma_{yy}\sin\theta + \tau_{xy}\cos\theta\right)\left(\Delta B\cdot\Delta t\right) \tag{3}$$

From equilibrium of forces in the *t* direction on the force wedge, we obtain the shear stress, $\tau_{n\theta}$ as a function of σ_{yy}, τ_{xy} and θ; where the shear plane, *t* inclination angle, θ = 38.7°, σ_{xx} = 0.

$$\tau_{n\theta} = -\sigma_{xx}\cos\theta\sin\theta + \sigma_{yy}\sin\theta\cos\theta + \tau_{xy}\left(\cos^2\theta - \sin^2\theta\right) \tag{4}$$

These theory were stated in Mueller and Krobjilowski [3] based on the generalised concept of the process zone that the actual crack length is extended by the length of the process zone which is taken is equal to a damage zone at the crack tip. Hence, for a crack length of *a*, the critical stress, σ_C is determined according to the stress intensity factor criterion, expressed by;

$$\sigma_C = \frac{K_{IC}}{\sqrt{\pi\left(a+\ell\right)}} \tag{5}$$

where ℓ is the damage zone at each crack tip.

3. Results and Dıscussıons

Table 1-2 shows mode I and mode II stress intensity factor (K_I) at different laminate thickness for 14 specimens; Table 3 shows mode I stress intensity factor (K_I) and critical stress for all 14 specimens Table 4 shows mode II stress intensity factor (K_{II}) and shear stress for all 14 specimens respectively.

Furthermore, Figure 3 shows mode-I stress intensity factor (K_I) curve at different crack length for all specimens; Figure 4 shows quadratic relation of mode-I stress intensity Factor (K_I) curve at different critical stress level for all specimens while Figure 5 shows Linear relation of mode-II Stress Intensity Factor (K_{II}) curve at different Shear Stress level for all specimens.

Table 1: Mode I Stress Intensity Factor (K_I) at Different Laminate Thickness for 14 Specimens.

Laminate Specimens	**Laminate Thickness, *B* (mm)**	**Mode II Stress Intensity Factor (SIF), K_I (MPa.m$^{1/2}$)**
A	4.4	9.32
B	5.2	6.57
C	4.5	9.49
D	6.4	6.41
E	7.1	6.59
F	5.7	6.59
G	7.7	6.65
H	8.4	4.47
I	10.3	3.02
J	6.8	4.87
K	7.32	4.68
L	7.2	6.17
M	10.2	6.7
N	13.5	4.86

Table 2: Mode II Stress Intensity Factor (K_{II}) at Different Laminate Thickness for 14 Specimens.

Laminate Specimens	**Laminate Thickness, *B* (mm)**	**Mode II Stress Intensity Factor (SIF), K_{II} (MPa.m$^{1/2}$)**
A	4.4	2.42
B	5.2	1.77
C	4.5	2.49
D	6.4	1.68
E	7.1	1.83

F	5.7	1.78
G	7.7	1.75
H	8.4	1.18
I	10.3	0.81
J	6.8	1.31
K	7.32	1.25
L	7.2	1.63
M	10.2	1.75
N	13.5	1.28

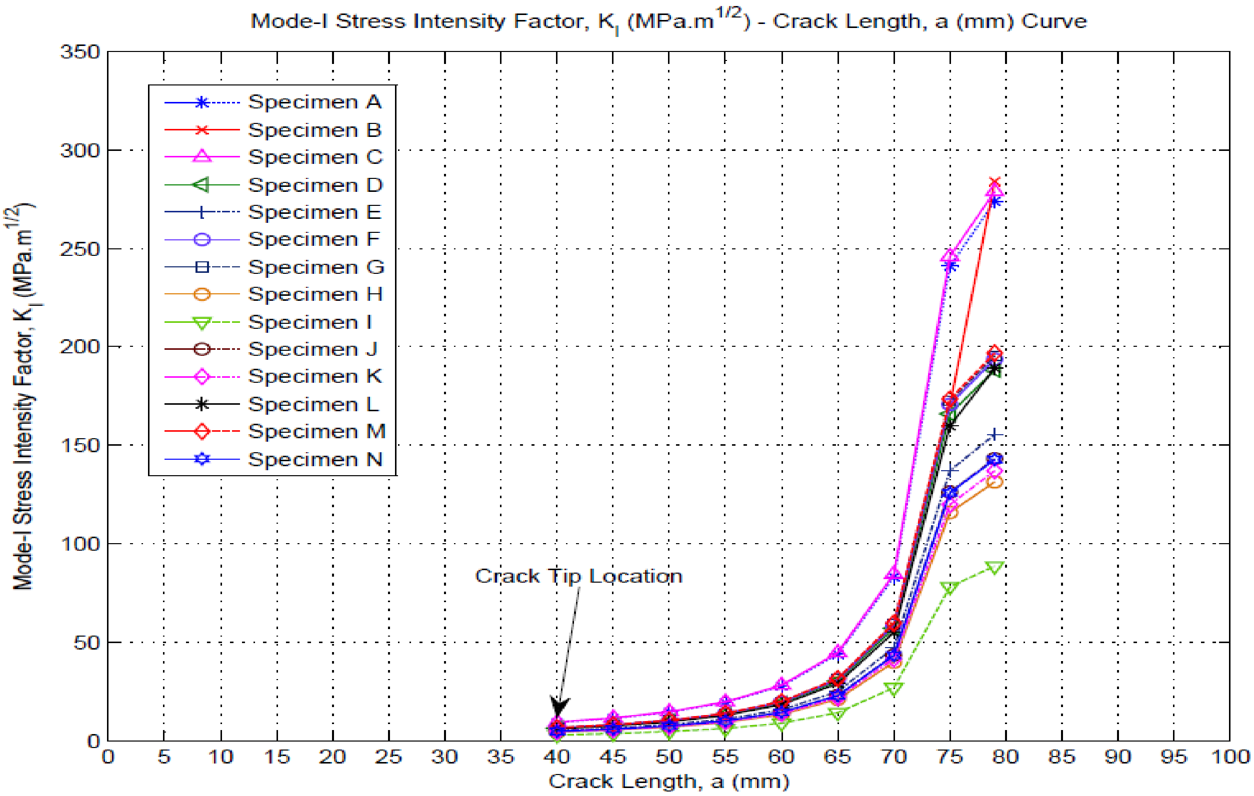

Figure 3: *Mode-I Stress Intensity Factor, K_I (MPa.m$^{1/2}$) Curve at different Crack length, a (mm) for all specimens*

Table 3: Mode I Stress Intensity Factor (K_I) and Critical Stress for all 14 Specimens

Laminate Specimens	Mode I Stress Intensity Factor (SIF), 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

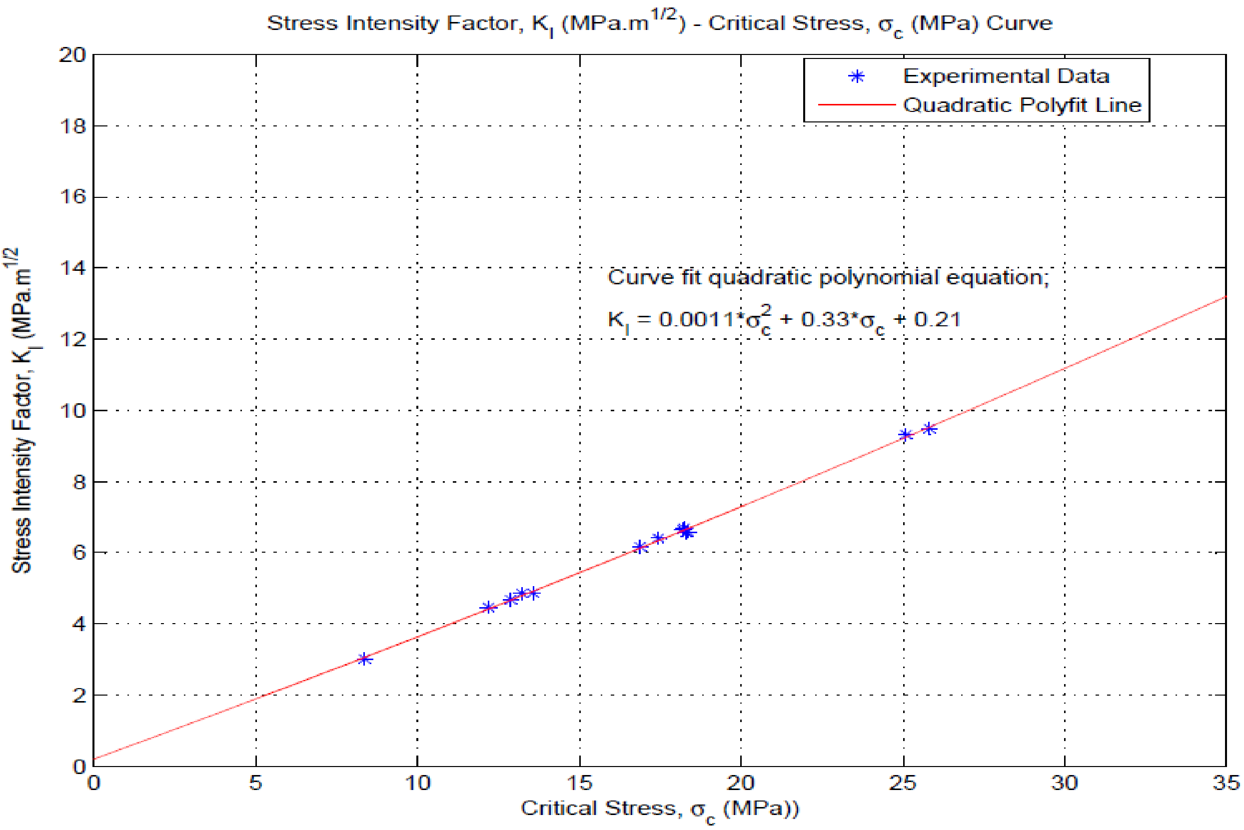

***Figure 4**: Quadratic Relation of Mode-I Stress Intensity Factor* (K_I) *Curve at Different Critical Stress Level for all Specimens*

Table 4: Mode II Stress Intensity Factor (K_{II}) and Shear Stress for all 14 Specimens

Laminate Specimens	Mode II Stress Intensity Factor (SIF), 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

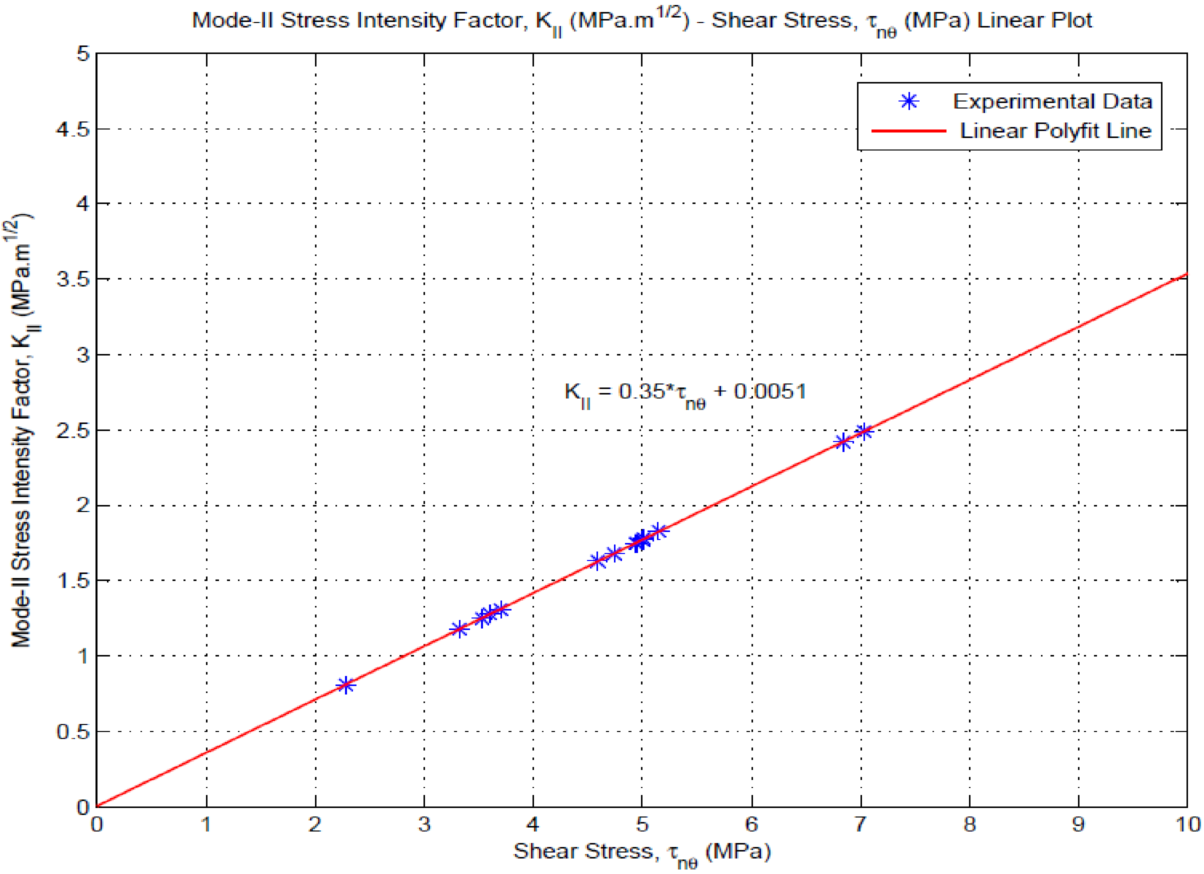

Figure 5: *Linear relation of Mode-II Stress Intensity Factor (K_{II}) Curve at Different Shear Stress level for all specimens*

3.1 Analysis of Stress Intensity Factors (K_I and K_{II}) and Critical Stress at Different Laminate Thickness

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 was manifestation of the size effect of which details were found in the work of Griffith. This could be sufficed to 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 4 and 5, 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 [10].

As show in Figure 3 of the plot for the mode I stress intensity factor versus crack length, it was found that the behaviour of mode I stress intensity for the various reinforced composite was influenced by the crack length, as well as the thickness, B and load, P which directly affects its magnitude. From Equation 1 and 2, it could be established that the stress intensity factor is a function of the presence of a crack on the composite structure, and that the magnitude of the load, P and the thickness of the specimens influences the rate of crack propagation in the specimens. Specimen I was found to have the smallest stress intensity factor with a thickness of 10.3mm and maximum load of 0.91kN. This could be traced to the form and volume fraction of reinforcement. But Specimen C was observed to possess the optimal stress intensity factor of 9.49 MPa.m$^{1/2}$ and 2.49 MPa.m$^{1/2}$ for mode-I and mode-II respectively (Table 1 and 2), that is, it has the highest tendency for crack to propagate due to excessive build-up of stress around the crack tip at every stage, as this could be traced to the composition of reinforcement. These results compared favourably with the result obtained by Radif et al,.[1] and Szekrényes [4] with a value of 8.2 MPa and 5.6 MPa respectively. The difference in results is due to the difference in composition and materials used in the studies.

4. Conclusion

The investigation of stress intensity factors of a reinforced polymeric composite (reinforced polyester composite) at different fracture modes had been achieved. From the experimental data obtained and the various plots deduced, specimen C was observed to possess the highest optimal stress intensity factor of 9.49 MPa.m$^{1/2}$ and 2.49 MPa.m$^{1/2}$ at critical stress of 25.82MPa and 7.12MPa for mode-I and mode-II respectively. Therefore, specimen C had the highest tendency for crack to propagate due to excessive build-up of stress around the crack tip at every stage, as this could be traced to the composition of reinforcement. It was also observed 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 micro-cracks 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 critical stress was observed to be very high for reinforced polyester composite specimens with smaller thickness compared to those with higher thickness, which showed lower critical stress values.

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