



*Journal of Engineering for Development, Vol. 13(1), October (2021) pp.26-37*

**INVESTIGATION OF THE FRACTURE MECHANISM OF REINFORCED  
POLYESTER COMPOSITE WHEN SUBJECTED TO SUDDENLY APPLIED  
FORCE**

**<sup>1</sup>Olodu D. D and <sup>2</sup>Ihenyen O. I.**

<sup>1</sup>Department of Mechanical Engineering, Benson Idahosa University, Benin City, Edo State, Nigeria

<sup>2</sup>Department of Production Engineering, University of Benin, Benin City, Edo State, Nigeria

<sup>1,2</sup> E-mail: [dolodu@biu.edu.ng](mailto:dolodu@biu.edu.ng), [imevbore.ihenyen@uniben.edu](mailto:imevbore.ihenyen@uniben.edu)

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**ABSTRACT**

*This study focused on the fracture mechanism of reinforced polyester composite when subjected to suddenly applied force. The experimental and analytical method was used which was based on impact and Linear Elastic Fracture Mechanics (LEFM) test procedures. Randomly varied combination of E-glass fibre in forms of woven roving, hard and soft mat was used as reinforcement in polyester resin matrix to manufacture test specimens (Composites). Fourteen test samples with geometry 210 mm x 150 mm were fabricated using hand lay-up method. They were cut and tested in accordance to ASTM standards for composite polymeric material tests under mode I and Charpy impact test conditions using the compact tension and the Charpy impact test specimens respectively. The results obtained from the investigation shows that the optimum load for specimens range from 0.90KN to 2.00KN. From the results' analysis, the specimens containing woven roving reinforcement were found to possess higher fracture toughness and resistance to both fracture and impact damage during the impact test. The specimens containing woven roving resist impact damage and failure due to the fibre stacking sequence, and this resulted in fibre pull-out during fracture.*

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**Keywords:** E-Glass Fibre, Reinforced Polyester Composite, Fracture Toughness, Impact Damage.

Article Information:

Received 19 September, 2021

Revised 27 October, 2021

Accepted 29 October, 2021

Available online 08 March, 2022

## 1.0 INTRODUCTION

The discovery and introduction of glass reinforced polyester composite material as a structural engineering material in the early 1950s had found wide application in automobile, energy, marine, military, building, electronics, aerospace engineering, household appliances and as structural engineering material [Olodu and Osarenmwinda, 2018; Idicula et al., 2009]. Radif and Ali [2001] examined the use of glass reinforced composite materials by manufacturers, from their study, it was observed that the material had high mouldability, good strength to weight ratio of the combined constituents and cheap to manufacture. Edelugo [2009] stated that during the service life of reinforced polyester composite, they are exposed to varying intensity of loading and environmental conditions, as in the presence of oxidation and harsh acidic or alkaline environments which have seriously limited the use of engineering materials in various capacities, and these could also constitute a threat to their load carrying capacity which sometimes results in catastrophic failure if defects are not noticed and monitored. In a study to improve the impact strength of natural fibre reinforced composite by specifically designed materials and process parameters, Mueller and Krobji [2004] experimentally investigated flax, hemp, and kenaf fibres in polypropylene binder for all hybrid fleeces in which the blending ratios of natural fibre/polymeric fibres was varied from 50/50 to 70/30, the 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 which was reinforced by natural fibres and glass fibres were also determined. Ladeveze and Le Dantec [1992] studied the fracture toughness of laminated composites, and affirmed the energy required before the onset of fracture was unexpectedly large, that is, around five times larger for the separate al-foil layer. Other studies were focused on estimating the microstructure fracture mechanism and limited stability of fracture mechanism [Garro and Trotman, 1980; Mandel *et al.*, 1982].

This research therefore focused on the fracture mechanism of reinforced polyester composite when subjected to suddenly applied force.

## 2.0 MATERIALS AND METHODS

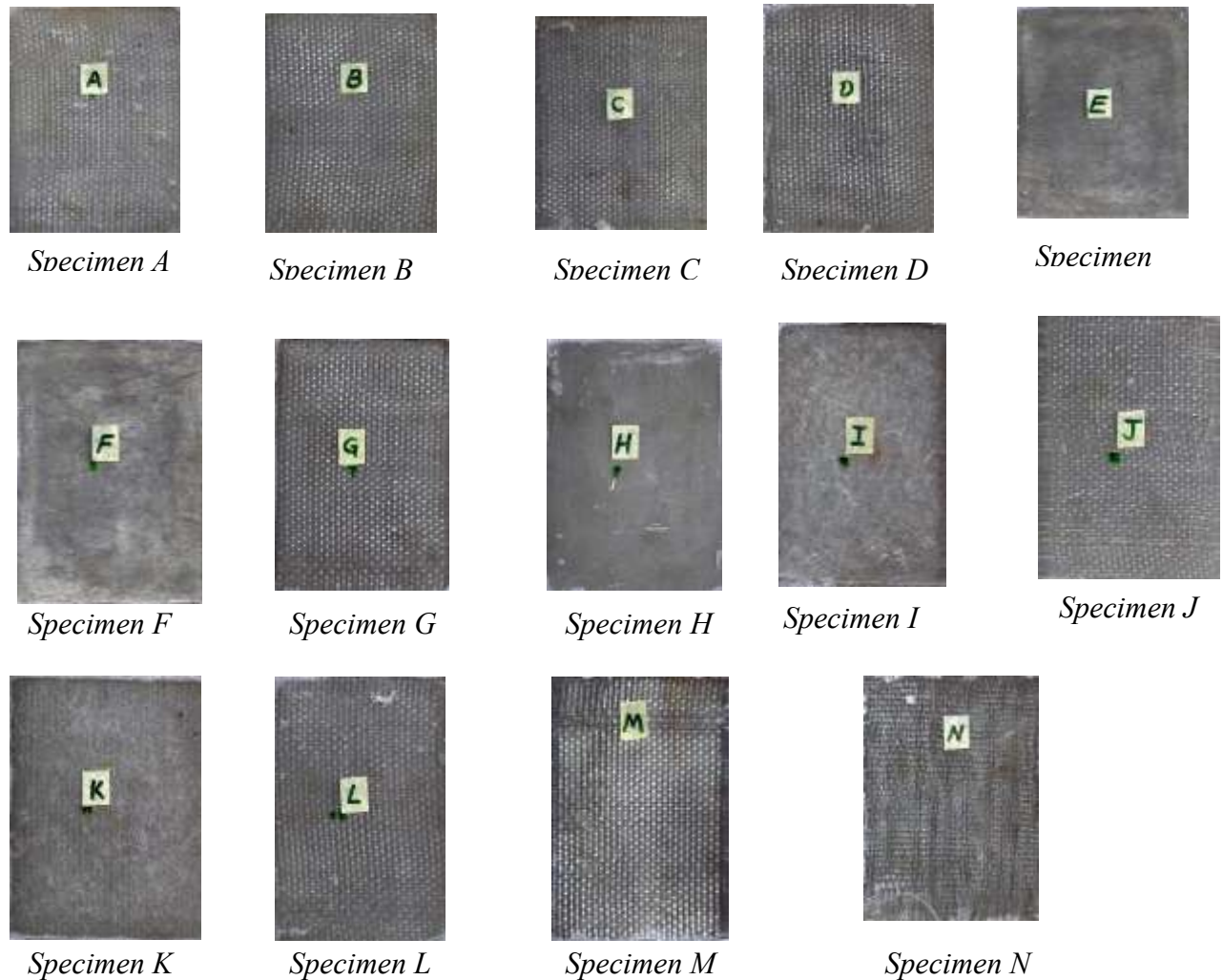
### 2.1 Materials

This research is 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. This was 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  $210\text{mm} \times 150\text{mm} \times 50\text{mm}$ . Hence, the reinforcement was impregnated with catalysed polyester resin, and allowed for a period of one month to completely cure at ambient condition. These samples for the tests was cut into 28 specimens, for which 14 samples were

compact tension (CT) specimen used for fracture mechanics test and the other 14 specimens were for impact tests respectively, using a hack saw cutting blade which was tested in accordance with the ASTM and ISO standard for fracture mechanics and impact tests respectively for composite materials. Figure1 shows the samples of manufactured reinforced Polyester composite plates.



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

### 2.3 Fracture Mechanics Assumptions in Reinforced Composite Analysis

The following fracture mechanics assumptions were made for reinforced composite analysis:

- 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.

## **2.4 Testing of Developed Composites**

### **2.4.1 Tensile Stress 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 [Parhizgar *et al.*, 1982]. The load sensing device had accuracy over a load range of within  $\pm 1\%$  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 was increasing, 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 LEFM requirements. Another purpose of notching and pre-cracking the test specimen is to simulate an ideal plane crack with essentially zero tip radius to agree with the assumptions made in stress intensity analyses. Each specimen test record consists 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. Destructive test method was used as the process was observed and studied under a video motion camera, making possible to monitor the damage as it progressed, crack propagation and final fracture of the specimen on a macroscopic scale level. Fracture and impact in composites result in permanent damage of the matrix and fibre, which further degenerate into fragmentation depending on the magnitude of stress intensity and concentration. It was observed that the roles of matrix in composite behaviour was to protect the fibres, enabling uniform distribution and transferring of stresses, thereby alleviating brittle failure by providing alternative paths for the crack growth along the ligament. This was observed to manifest in elastic deformation which was followed by irreversible damage and failure as could be traced to the heterogeneous nature of the material on a macro-scale. The results were carried out in two phases, namely; the compact tension (fracture) and impact tests. The maximum load before failure of the test specimens was determined.

### **2.4.2 The Charpy Impact Test**

The purpose of the Charpy impact test is to measure the energy absorption capacity of the reinforced polyester composite materials [Williams, 2020]. A notched bar of reinforced composite specimen was supported as a simple beam so that the vertical faces away from the point of impact and is struck at the middle using a hammer as incorporated on the test equipment. The impact test had a setup similar to the 3PB test and this is the most appropriate for the composite material, which damage and fracture in a brittle manner because of the presence of micro defect or a surface scratch; and the stress concentrated at these regions as this will accelerate the failure rate under sudden impact force. The energy which is absorbed by the blow is determined by a measuring device on the machine.

### 3.0 RESULTS AND DISCUSSIONS

#### 3.1 Fracture Mechanics (Compact Tension) Test Results Analysis

The fracture mechanics test was carried out using the compact tension specimen. The fracture was found progressively in a linear mode until abrupt failure occurs. Figure 2 shows the images of the fractured compact tension (CT) specimens after experimental test, while Figures 3-16 shows load – displacement curve and 5% Secant Offset Line for CT specimen.



*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 2: Fractured CT Test Specimen after test.**

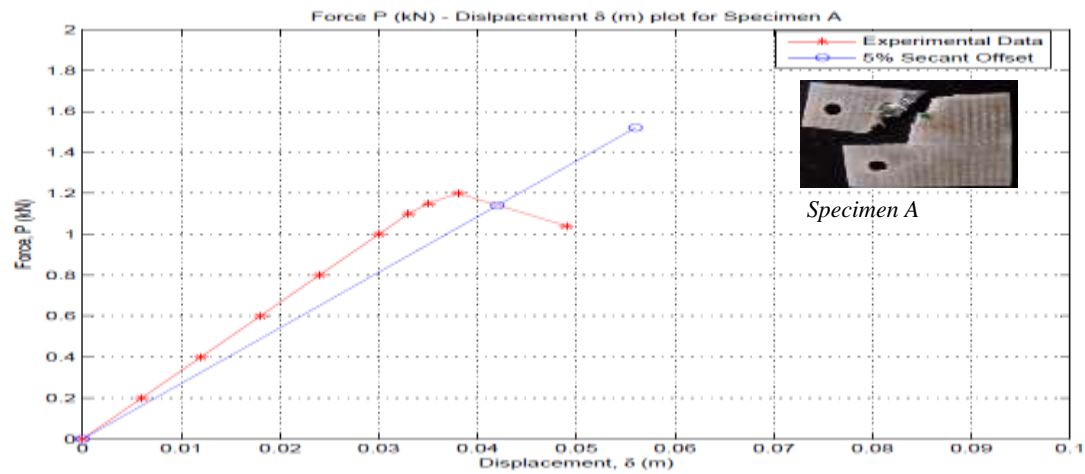


Figure 3: Load – Displacement Curve and 5% Secant Offset Line for CT specimen A

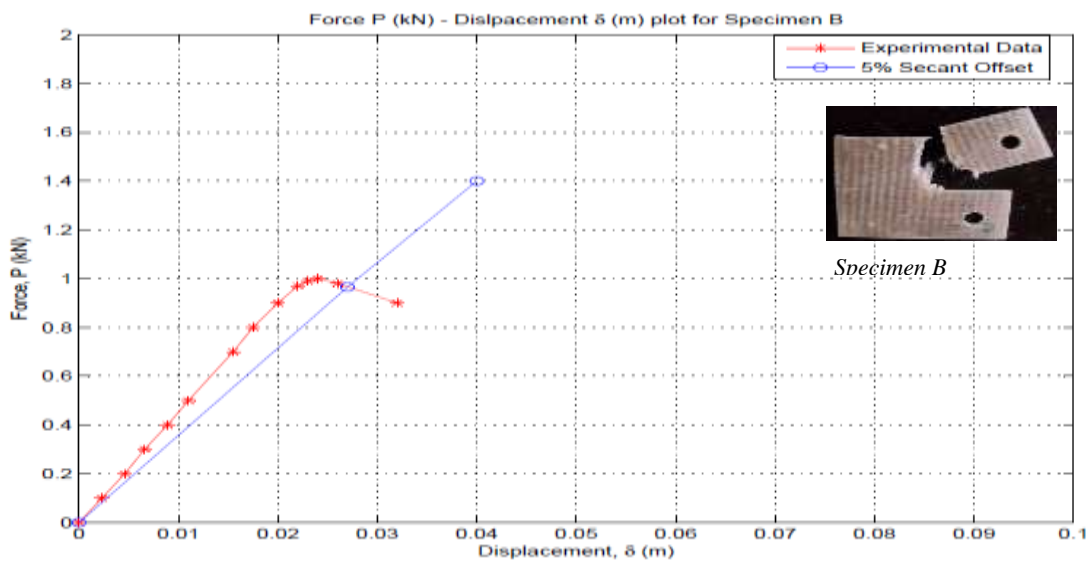


Figure 4: Load – Displacement Curve and 5% Secant Offset Line for CT specimen B

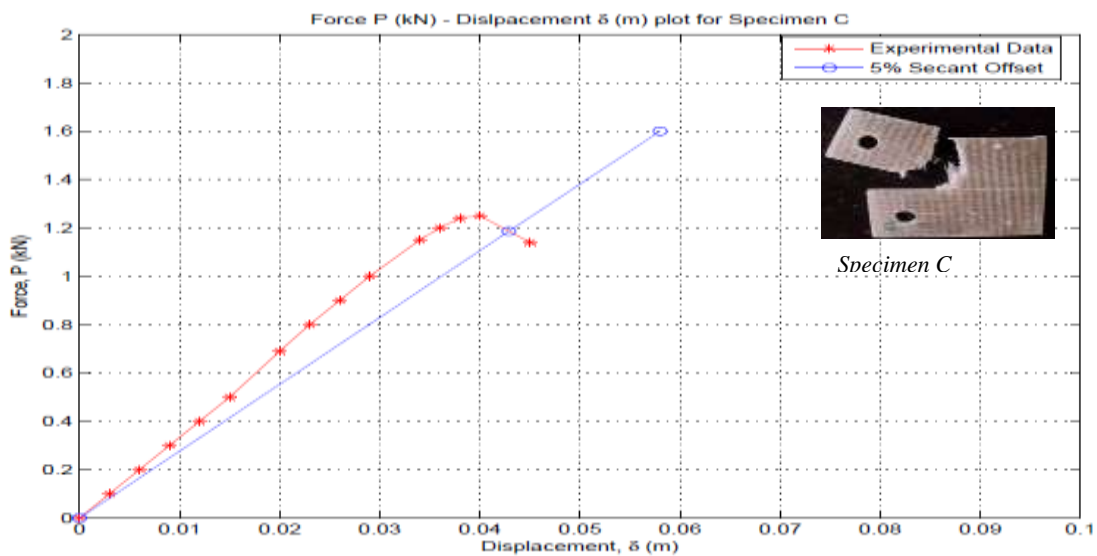


Figure 5: Load – Displacement Curve and 5% Secant Offset Line for CT specimen C



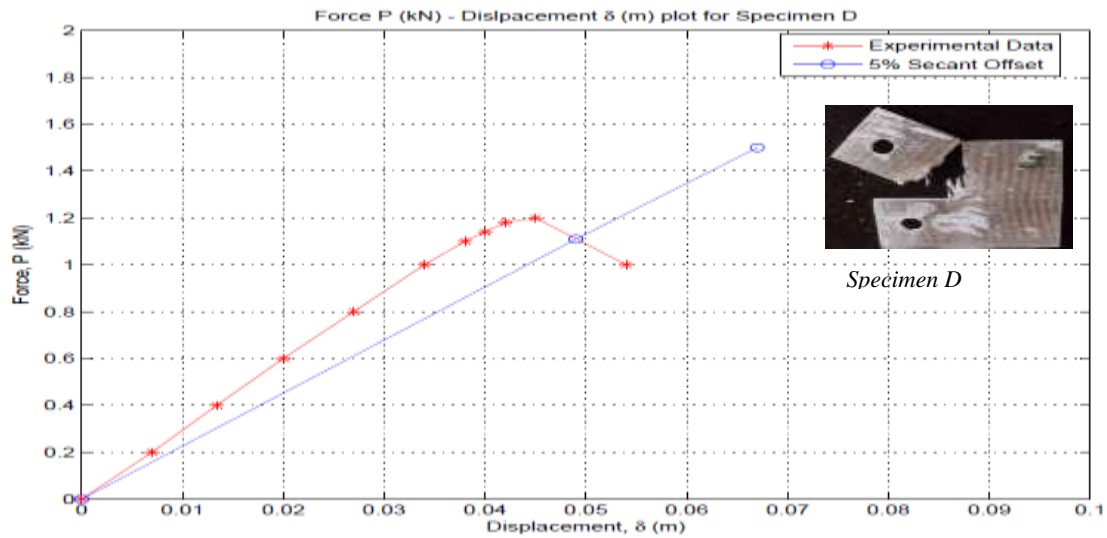


Figure 6: Load – Displacement Curve and 5% Secant Offset Line for CT specimen D

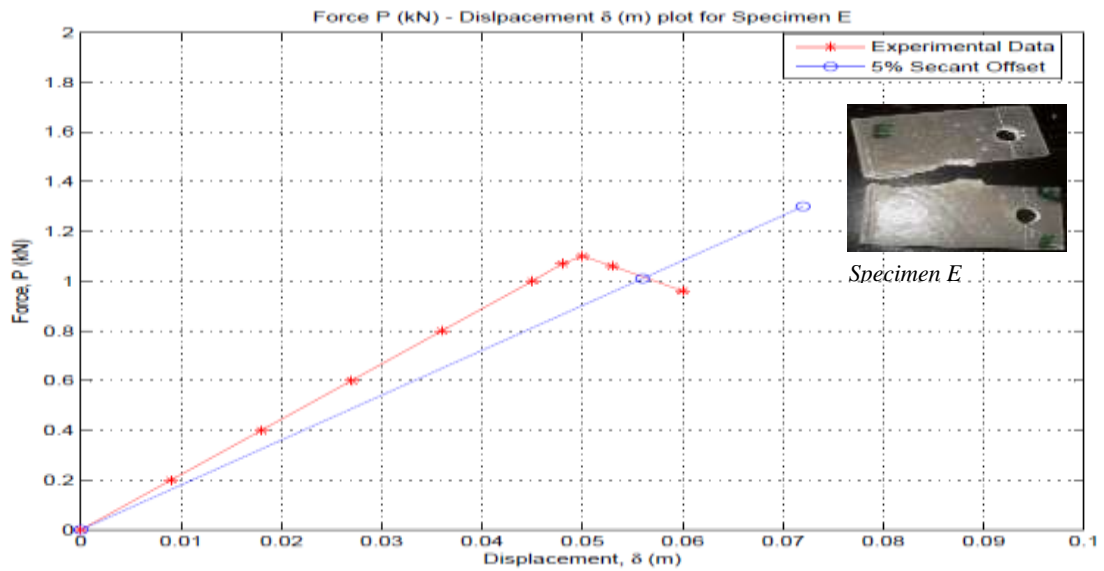


Figure 7: Load – Displacement Curve and 5% Secant Offset Line for CT specimen E

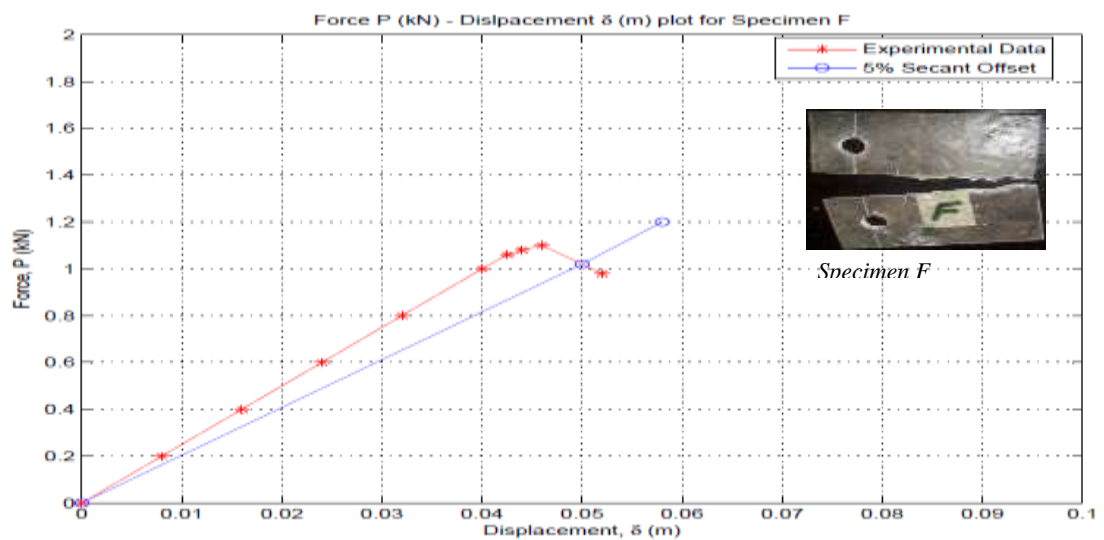


Figure 8: Load – Displacement Curve and 5% Secant Offset Line for CT specimen F

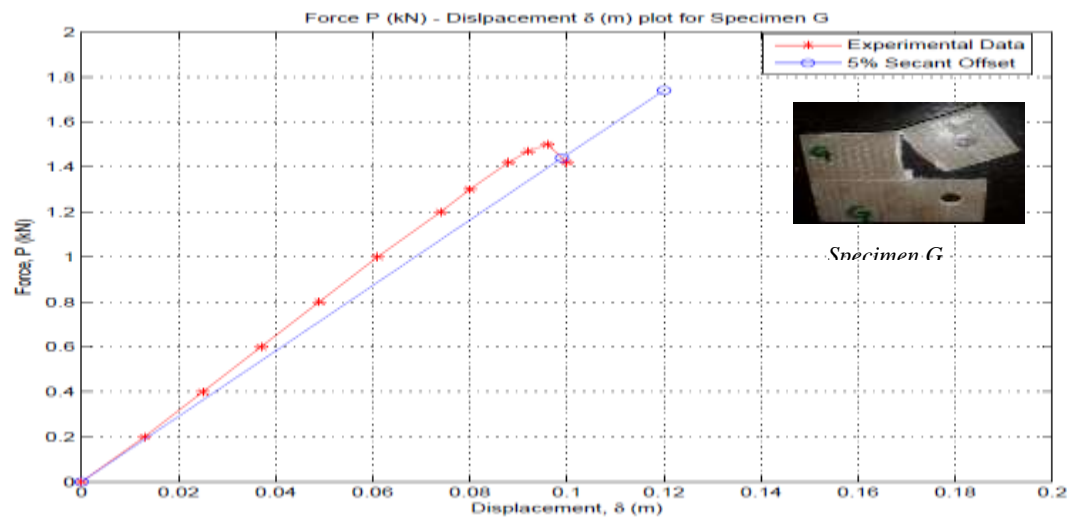


Figure 9: Load – Displacement Curve and 5% Secant Offset Line for CT specimen G

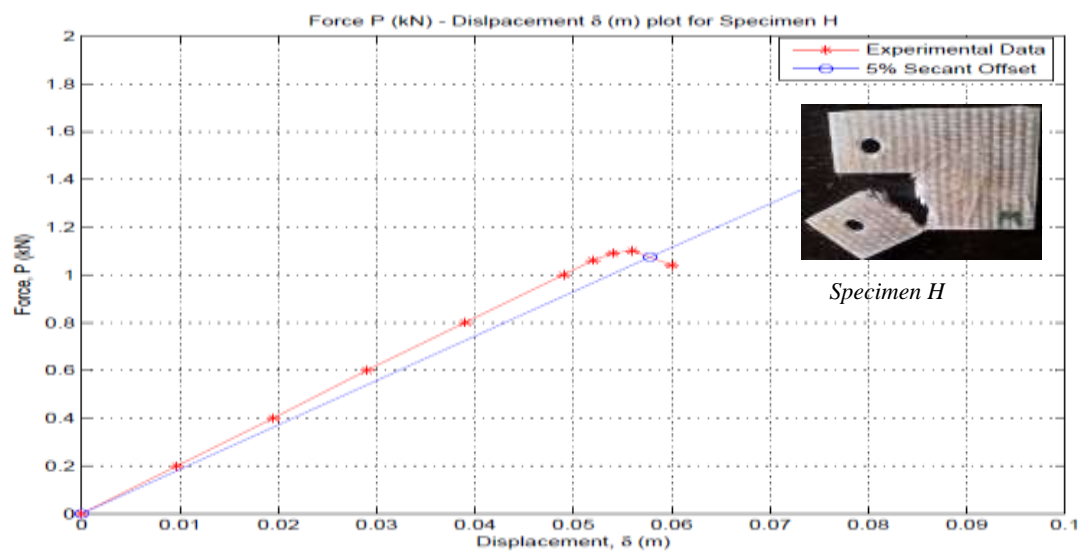


Figure 10: Load – Displacement Curve and 5% Secant Offset Line for CT specimen H

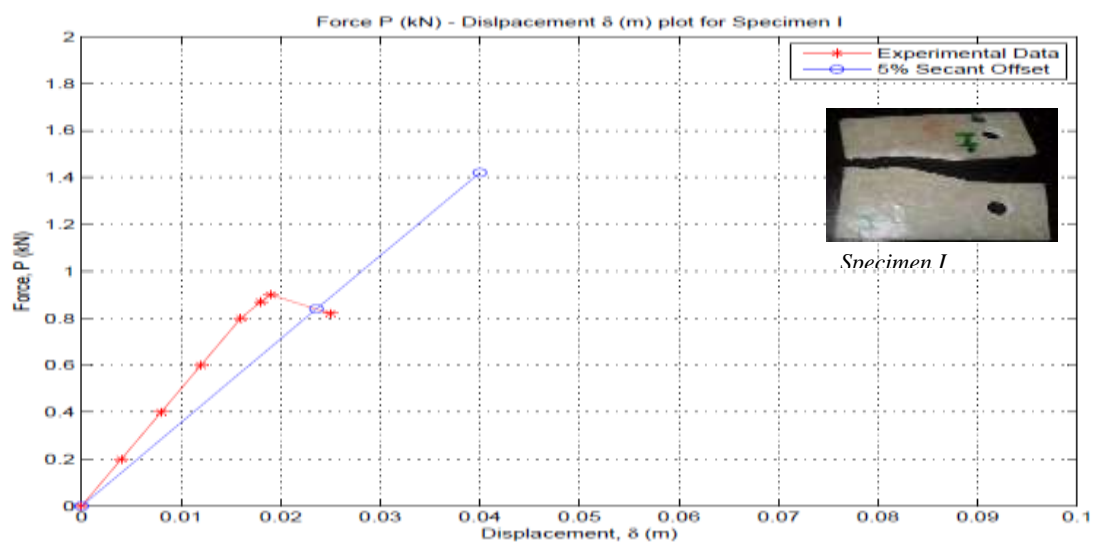


Figure 11: Load – Displacement Curve and 5% Secant Offset Line for CT specimen I



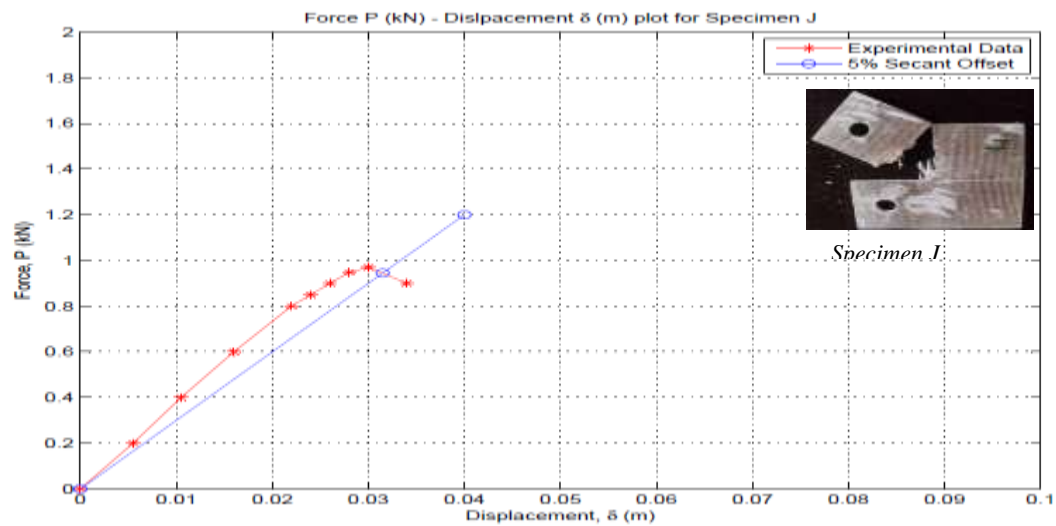


Figure 12: Load – Displacement Curve and 5% Secant Offset Line for CT specimen J

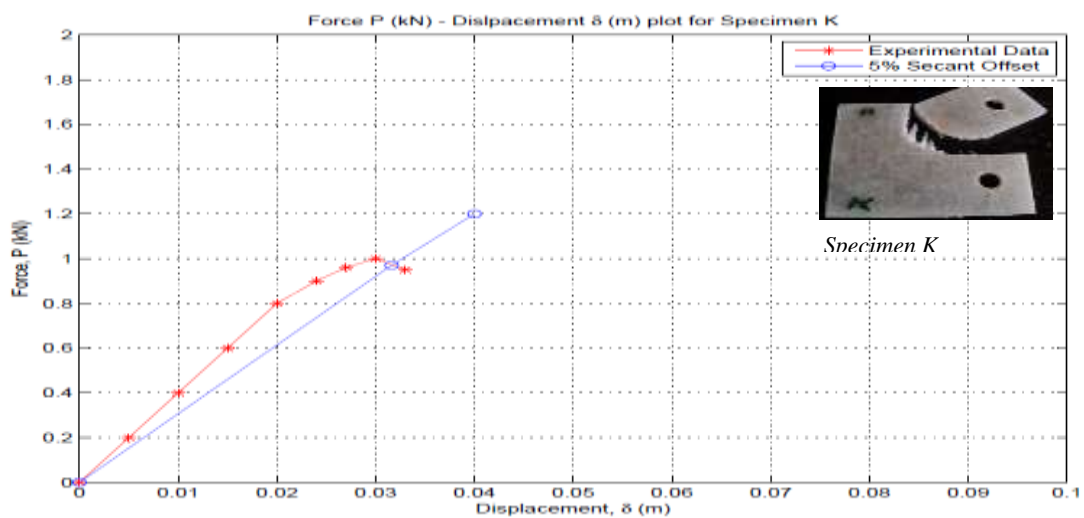


Figure 13: Load – Displacement Curve and 5% Secant Offset Line for CT specimen K

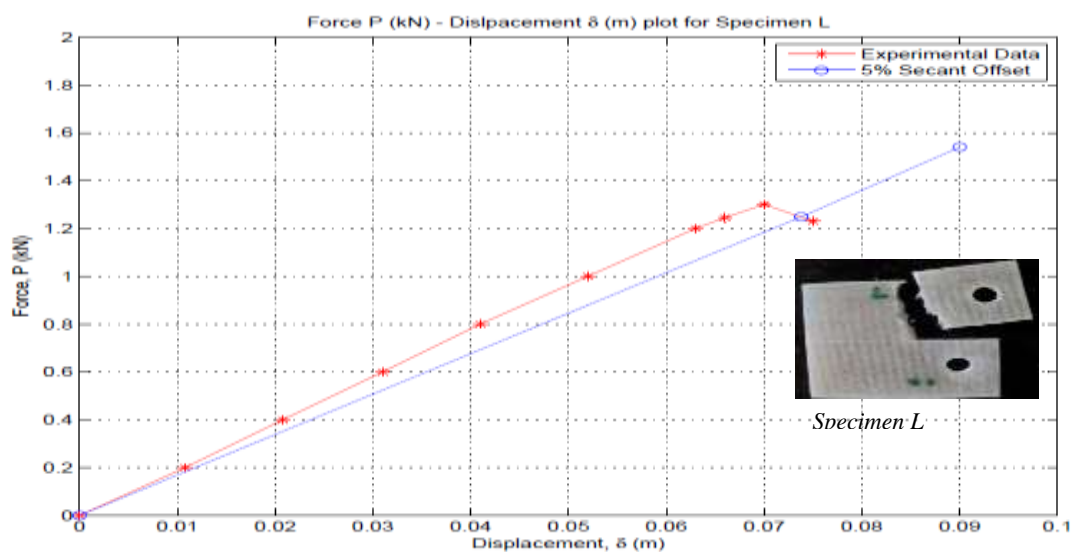


Figure 14: Load – Displacement Curve and 5% Secant Offset Line for CT specimen L

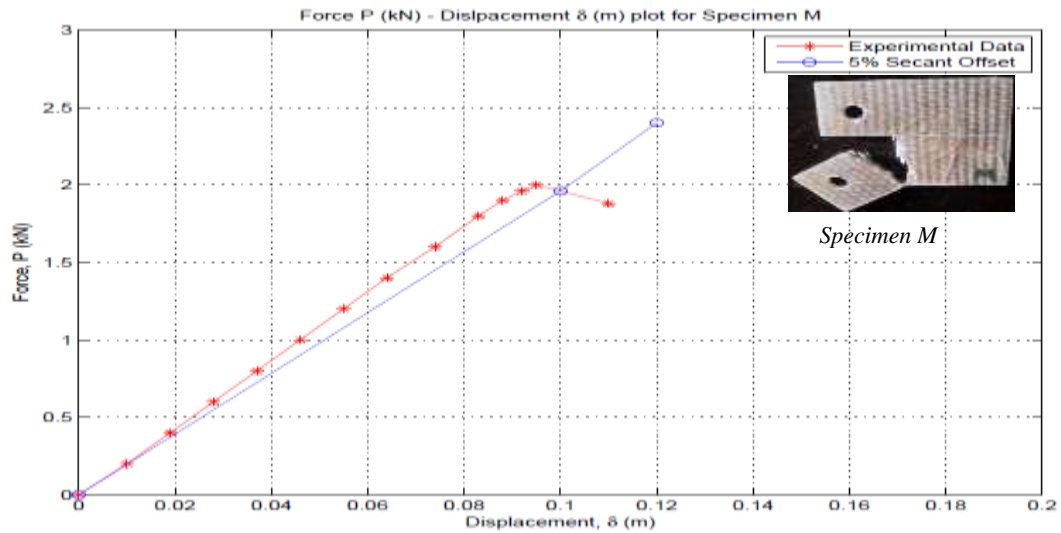


Figure 15: Load – Displacement Curve and 5% Secant Offset Line for CT specimen M

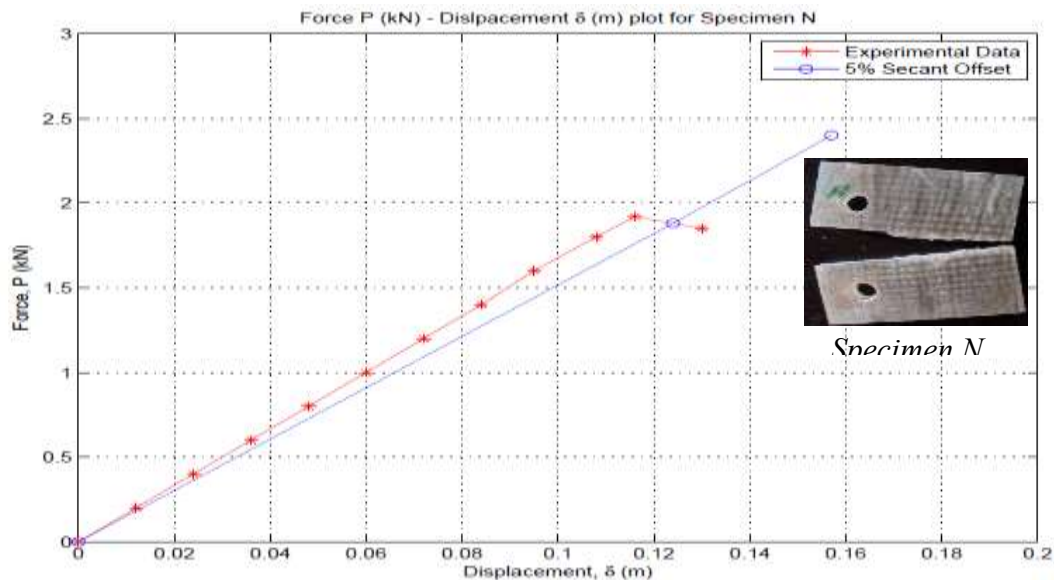


Figure 16: Load – Displacement Curve and 5% Secant Offset Line for CT specimen N

### 3.2 Load, $P$ (kN) versus Displacement, $\delta$ (m) Test Data and Plots

The load – displacement plot was obtained for all specimens from experimental data, and this provided the platform for the fracture mechanics analysis on each specimen, containing varied fibre volume fraction and form, using the compact tension specimen, as shown above under tensile load condition on the universal testing machine (figure 3-16). As the load was gradually applied and varied at a constant rate of 0.55mm per minute, then the crosshead vertical displacement data obtained as well as the increase in crack length as it propagated along the ligament and a successive interval of 5mm. These measurements were successful carried out by marking the crack growth front as it advanced. The determination of the maximum load,  $P$  leads to the determination of the stress intensities. From the results obtained, it was observed that the optimum load for specimen A, B, C, D, E, F, G, H, I, J, K, L, M and N are 1.1kN, 1.00kN, 1.25kN, 1.20kN, 1.10kN, 1.10kN, 1.50kN, 1.10kN, 0.90kN,

0.97KN, 1.00KN, 1.30KN, 2.00KN and 1.92KN respectively. From the review on the profiles and nature of the plots, the load was observed to vary in a linear fashion for all the specimens till near failure where the magnitude sharply dropped due to loss of strength in the region with smaller volume of material, insufficient to pose a resistance to the progressive deformation (figure 4-17). The magnitude of the force required to propagate the initial crack along the ligament at the onset of crack extension till failure was found to be higher for specimens containing woven roving glass reinforcement. This could best be credited to the nature of the weaving, resilience, area/weight ratio and volume fraction of woven roving present in the matrix. This was further influenced by the properties of hard mat which could also pose significant resistant to failure compared to soft mat which possess the least of strength among other reinforcements. These compositions were also found to influence the direction of the crack propagation, as the fracture test progressed with gradual increase in loading. Crack in specimen with dominant soft and hard mat reinforcement were found to propagate along the same direction with the initial crack, while some of the specimens containing woven roving were found to change direction as the crack propagation continued as shown above. The change in direction could best be attributed to fibre bridging within the matrix as the stress intensified around the region.

### 3. CONCLUSION

From the experimental result on the tests carried out on hybrid glass reinforced polyester composites exposed to sudden impact force, the optimum load for specimens range from 0.90KN to 2.00KN. It could be said that the varied compositions of reinforcement greatly influenced the behaviour, performance and response to impact force. It was observed that soft mat was more effective and efficient at the middle of the cross section and at the surface as a protective veil than other forms, this is because it is completely absorbed by polyester resin, thereby forming a homogeneous composite. Moreover, the hard mat was at its best performance at the sub layer just above the soft mat and below the woven roving, the woven roving fibres was observed to be a major player with respect to impact performance due to its fibre length, bundle size, compactness ratio, weaving and its rigidity. From the experimental data obtained and the various plots deduced, it could be established that on exposure to sudden impact force, reinforced polyester composite has the tendency to fracture in a rapid manner if inappropriate and inadequate fibre content and combinations are not given careful consideration.

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