Comparative studies of experimental and numerical evaluation of tensile properties of Glass Fibre Reinforced Polyester (GFRP) matrix

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ARTICLE INFO
Keywords:
Young's modulus
SciLab software
Statistics
Tensile properties
Irradiation
Fibre polymer matrix
T-test

ABSTRACT
The investigation and comparative analysis of Chopped Strand Mat Glass Fibre Reinforced Polyester (CSM/GFRP) composite laminates was conducted. The laminate samples for the experiment were first exposed to diverse X-rays intensity rates at 6 mAs interval before test under cryogenic temperature. The generated values for tensile properties like young's modulus, strength, force, energy and elongation values were all measured and noted. The tensile modulus presented 43.8% decrease at the first 12 mAs exposure before it started increasing in the order of 30.3%, 6.3% and 12.3% respectively. Also, a science laboratory (SciLab) numerical evaluation of the material's tensile young's modulus was carried out and the obtained values compared with the experimental result to ascertain the level of relationship between the two approaches. It was observed that all the tested tensile properties were not consistent in the line of material strength depreciation values, apart from tensile young's modulus. The latter is consistent, but when considered with numerical model; their values became inconsistent like the former. However, when Analysis of Variance (ANOVA) for both approaches (experimental and SciLab numerical evaluations) were checked using t-test for pair comparisons, the data sets produced a computed t-value of 4.51. The obtained t-value and the critical t-value of 2.57 for 5% level of significance and 5-degree of freedom were compared, and it was noticed that the obtained t-value was higher than the critical t-value which indicated that the result was significant at the 5% level. Thus the null hypothesis is rejected which suggests that both approaches were relevant to tensile properties investigation at cryogenic temperature.

1. Introduction
Applications of Glass Fibre Reinforced Polyester (GFRP) elements have become more popular in several areas of engineering in recent years. It is essential in Engineering to conduct test on any new material on the basis of where and what purposes it intends to satisfy. Thus, the evaluation of their tensile properties is imminent for the application of such types of composite laminates in the industries. In this case, mechanical application of the produced composite laminates is the target. Their properties relied on the composite structure (i.e laminates pattern) [1,2] and the conditions at which the investigation is done such as the environmental influence [3,4], amount of strain [5], temperature and the type of the load applied [6,7,8]. There are a lot of factors that constitute the strength of composites; they are as follows: the boundary layers of the fibre components, the volume fraction that is taken as a result of the differences in laminate pattern [9], and also the mixing ratio of their catalyst and accelerator used to polymerize the resin matrix [10]. Furthermore, it is relevant to note that tensile tests have been the most populous technique for describing the mechanical reaction of composite elements for several years. Nevertheless, there is no reliable direct method at the moment for tensile tests on composite laminate at a low temperature. Determining the composite tensile properties, mainly the ultimate strength, at low temperatures is not direct [11,12]. This was caused by the high strength, toughness etc. Generally, low temperature tensile investigations on polymer matrix composites have shown visible irregular occurrences in respect to the values of strength [13,14]. Also, low temperature testing problems equally involve the specimen falling out of the test holder during the test. Trying to increase the fastening torque to avoid the holder slipping could lead to the accelerated concentration of the stress level within the grip location which affects the strength of the data measured. To address the issues associated with low temperature tensile examination, investigators have engaged their time in appraising the low temperature mechanical tension response of composite laminate. Take for an instance the work of Kumagai et al. [12],

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https://doi.org/10.1016/j.heliyon.2021.e06887
Received 20 June 2020; Received in revised form 15 October 2020; Accepted 19 April 2021
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they performed experiment and numerically tested the effect of specimen geometry and holding pattern on the tensile properties of woven GFRP laminates with high glass make-up at low temperatures. Shindo et al. [15] also examined the low temperature mechanical reaction of woven GFRP laminate specimens and analyzed the effect of specimen shape and size on the material behaviours under tension. Hongshuai et al. [16] conducted experimental and numerical investigation in the macroscopic mechanical behaviour of shape memory Alloy Hybrid Composites (SMAHCs) with consideration of weak interface effect and damage evaluation. In their report, it was established that the material exhibited a bilinear mechanical behaviour. Azim [17] investigation on the effect of gamma radiation on the properties of Jute Reinforced Polyester Matrix (JRPM) revealed that irradiation doesn’t always negatively influence the mechanical properties of composite material, especially when radiation dosage (intensity) is the unit for consideration. The experiment highlighted the earlier cross-linkage reaction among the constituent materials of the composite laminate and subsequent secession reaction resulted by increased dose of radiation. Akabe et al. [18] studied the crack formation on the free edge of Composite Fibre Reinforced Polyester (CFRP) cross-ply laminates stress and failure analysis; and the results measured by the Digital Image Correlation (DIC) technique, suggested that crack formation is assumed to occur in the matrix by the dilatation induced brittle failure mechanism. Chiachin et al. [19] investigated the early damage, continuous damage scrutiny, and the result of structure on strength of laminates by applying Hashin's principle. They developed a three-dimensional model of composite laminates that was notched at the middle and involved the model to mimic the entire process of the early damage, growth of damage, and scrutiny of the result of a few structures on strength of notched composite laminates. Chiachin et al. [19] concluded that the growing damage and damage level of the matrix is lock up to the point of stress concentration where it grows with additional increase of applied load or dislodgment to reach the tensile strengths. Singh et al. [20] conducted numerical and experimental analysis on mechanical properties of composite laminates that was made of pure epoxy and random orientated glass fibre of different weight fractions of glass fibres. The experimental results obtained revealed that the tensile properties accelerated with the increase in weight fraction of fibre reinforcement. They later compared the generated numerical result with the former, and observed that the two approaches were in good agreement with each other. Shindo et al. [21] in their ingenuity introduced open-hole on composite laminate specimens to decide stress rising locus. They conducted tensile test and performed a microscopic examination on fractured surfaces of the failed specimens, which revealed that a high damage zone developed at the hole edge before further damage. Also, they performed another experiment on unnotched composite laminate specimens and estimated their cryogenic tensile properties using finite element analysis model. In this way, they were able to present a new method for evaluating and obtaining the consistent and reasonable values of tensile properties of composite materials at low temperatures. Certainly, the introduction of open-hole tensile examination was to investigate the notched stress which is possible during composite laminate repairs. However, it is relevant to note that notched stress is composite structural property and not composite material property [22]. The open-hole specimen provides for stress concentration, which implies that the failure load of the notched specimen will be far less than the unnotched specimen. Therefore, the alternative in open-hole tensile test for composite tensile property at cryogenic temperatures is not yet a better presentation for composite material property.

Due to what transpires in the composites that are filled with fibre, the damage mechanisms which comprise fibres breakage, failure of the matrix along the fibres, breakage of the fibres in the boundary layers, the process linkages that warrant damage of composite laminate is caused by the specimen’s angle between the fibres [23]. Thus, isophalic polyester based polymer composite laminates will be investigated for tensile properties. A combined experimental-numerical computational method will be presented for the evaluation of the tensile properties of chopped strand mat GFRP composite laminates. Six samples of composite laminates will be prepared with equal fibre concentration and subsequently expose to X-rays radiation at different intensity. The tensile tests will be conducted at room temperature and the force, young's modulus, energy to break, elongation and the strength value of each sample will be obtained. The experimentally determined and Scilab numerically computed values of the young's modulus (E) will be compared to ascertain the preferred and effective approach for tensile properties investigation. The null hypothesis will be predicted using t-test ANOVA tool.

2. Materials and methods

2.1. Material and specimen preparation

Six samples of A, B, C, D, E and F composite material laminates were produced using hand lay-up mould approach. The compositions of material in each laminate were carefully made such that each sample of the composite laminate possesses the same proportion of material ratio. Reinforcement of one ply of chopped strand E-glass fibre family was perfectly layered inside the mould after the application of wax (release agent) on the inner surfaces of the mould. The matrix aspect of the laminate is isophalic polymer based resin, which was activated by the presence of methyl-ethyl-Kato peroxide, and cobalt. The polymer based resin; methyl-ethyl-Kato peroxide and cobalt are mixed in the percentage ratio of 100:1:1. This mixture was stirred consciously to avoid air-bubbles presence--yet homogenous mixture was achieved. However, the impregnation of the fibre already layered inside the mould was carried out, hence the emergence of Glass-fibre-polyester-composite-laminate. The new material product was demoulded after 24 h of cure at room temperature. The same process was repeated until six samples of composite laminate were produced which was needed for this investigation. To ensure that we have quality material specimen profile, all the samples were subjected to compression mould of 2 KN force. It was then allowed for another period of 24 h to ensure that the formed composite laminates adjust to plain and flat surface laminates. In this way, the required material profile was produced for easy test-specimen preparation. Subsequently, post-cure treatment under diverse radiation dose of X-rays intensity was carried out as shown in Figure 1, and the material test-specimens prepared in line with the American Society for Testing and Materials standard (ASTM 3039) [24]. The X-ray machine used is ATOMAX-2 100/85 Tpe C model. A voltage of 70 Kv at the X-ray tube and system tube current of 100 mA were selected and the Focal Specimen Distance was set to 90 cm FSD [25].

The intention was to evaluate the tensile properties of this new material which was processed at cryogenic temperature. So, the material sample specimens were prepared—one out of each sample. It was paramount for the state of the art technology to be stated; thus, American Society for Testing Materials method was engaged for the material characterization. The specimen’s geometry and size that was required by the testometric machine was noted and shaped in consonant with the standard specification, such that no initial crack or fibre distortion was present. The dimensions are 300mm in overall length (L), 20mm in width (W) and 6mm thickness (b). It was achieved using band saw.


2.2. Material characterisation

The influence of radiation on the fabricated material was the locus to which the material’s property variation was made. Each specimen out of the six separate material samples that were treated under different radiation dose was tested. A careful specimen setup was made on the M500 25CT model testometric machine, it was arranged in a manner in which the specimen setup was made on the M500 25CT model testometric machine, it was arranged in a manner in which the specimen was found to have experienced deformation as soon as there was increase in tension load. This deformation occurred gradually at the middle part of the specimen as the applied load increased at a constant rate along the material axis.

During this process, the force (F) applied to deform the specimen was measured by the Testometric machine and the stress (δ) required was obtained by simply using the cross-section area (A) to divide the measured force (F)\(^{[26]}\). See Eq. (1).

\[
\delta = \frac{F}{A} \tag{1}
\]

Similarly, strain (ε) equally can be gotten by considering Eq. (2)\(^{[26]}\).

\[
\varepsilon = \frac{\Delta L}{L_0} \tag{2}
\]

Thus, Young’s Modulus (ε) can be calculated using Eq. (3)\(^{[26]}\).

\[
\varepsilon = \frac{\Delta L}{\varepsilon} \tag{3}
\]

Where

\(\Delta L\) is the change in length of the test-specimen and

\(L_0\) is the initial gauge length

For many mechanical properties examination, Universal Testing Machine (UTM) like the testometric machine has been very useful. The upward movement of the crosshead of UTM was what stretched the specimen. And the amount of the applied force on the specimen was recorded by the load cell. The extensometer determined the strain of the specimen which took place at the uniform cross-sectional region of the gauge length. The monitor of the computer system unit which was attached to the UTM provided the data output of the entire required parameters, including force and elongation curve of each sample test-specimen as shown in Figure 4.

2.3. Numerical evaluation

Science laboratory 5.5.2 console computer software was used to programme Young’s modulus model in (equation 4). Each sample was examined by carrying out experimental data simulation of all the test-specimens. The values obtained were recorded in (Table 2) for onward comparison with the experimental values.

\[\text{function } y = f(l); \text{ } y = (q / (l / 200)); \text{ endfunction} \tag{4}\]

Where

\(y\) is the new product of young’s modulus,

\(q\) is the experimental tensile strength,

\(l\) is the change in length of the test-specimen and

\(200\) is a constant for specimen gauge length

2.4. Test of significance using t-test on paired comparison

To compare the scilab numerical result and the experimental result, t-test on paired comparisons as ANOVA tool was deployed. We adopted test of hypothesis and significance which stated that any guesses which may be true or false about probability distribution of populations carried out in order to arrive at a point is assumed to be statistical theory— it may be taken as null hypothesis (equation 5) which is denoted by \(H_0\) or alternative hypothesis (equation 6) which is denoted by \(H_1\)\(^{[27]}\).

That is,

\[
H_0: \text{all } d_i = 0 \tag{5}
\]

Similarly,

\[
H_1: \text{all } d_i \neq 0 \tag{6}
\]

Thus, the outcomes of the analysis of the two methods were compared and a decision between the two theories, \(H_0\) and \(H_1\) was taken. Most importantly, the null hypothesis was taken to be the actual result until otherwise stated. This means that, the weight of the proof is on \(H_1\) and the departure started from \(H_0\).

For \(t\)-test on paired comparisons, in practice a level of 1% or 5% significance is common\(^{[27]}\). Mathematically, it can be expressed as follows in Eq. (7):

\[
t = \frac{\overline{d}}{s_d / \sqrt{n}} \tag{7}
\]

and

\[
\overline{d} = \frac{\sum d_i}{n} \tag{8}
\]

Also, standard deviation

\[
S_d = \sqrt{\frac{\sum (d_i - \overline{d})^2}{N - 1}} \tag{9}
\]

Where, \(d\) is the average difference of the two methods (equation 8), \(S_d\) is the standard deviation (equation 9), and \(t\) is the \(t\) – statistic, \(n\) is the number of sample treatment and \(d_i\) is the difference between methods of test \(M_1\) and \(M_2\)\(^{[27]}\). To conclude the test, the percentage point, \(t_{\alpha / 2}\) was read from the students – \(t\) distribution table\(^{[27]}\). At a specified level of 5% significance, the decision whether to welcome or reject the null hypothesis based on the computed \(t\) – value (in Table 3) was made.

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Table 1. Summary of the experimental results.

| S/No. | Force at peak (N) | Elongation at peak (mm) | Stress at peak (MPa) | Energy to break (N.m) | Young’s modulus (MPa) |
|-------|-------------------|-------------------------|---------------------|-----------------------|-----------------------|
| A     | 4324.90           | 3.53                    | 36.04               | 7.80                  | 2690.89               |
| B     | 3631.00           | 3.43                    | 30.25               | 7.18                  | 2321.75               |
| C     | 1651.70           | 1.81                    | 13.76               | 1.71                  | 1511.16               |
| D     | 2913.90           | 3.10                    | 24.28               | 5.36                  | 2169.46               |
| E     | 1932.80           | 2.28                    | 16.10               | 2.42                  | 2316.05               |
| F     | 3314.90           | 2.76                    | 27.62               | 4.74                  | 2641.77               |
3. Results and discussion

3.1. Presentation of results

Table 1 presents the samples' value for tensile properties like force at peak, elongation at peak, stress at peak, energy to break and Young's modulus. The specimen's test-value for each property behaved alike. With close observation, it was noticed that sample-A without X-ray exposure has the highest value more than the exposed samples. Sample-B which was exposed for about 6 mAs shows that there is a decrease of value in the material tensile properties across board. Sample-C demonstrated further material degradation for dropping drastically in its values as a result of 12 mAs dose of X-ray intensity. The sample-D on the contrary, took different direction which suggested that the material at this level of x-ray dose of 18 mAs gained an appreciable material stiffness. The following sample-E in the contrary to the latter decreased among all the tensile properties except the young's modulus. Moving down further in the table, we discovered that every other tensile property continued to fluctuate by irregular values occurrence [13, 14]. But in the part of young's modulus, the values maintained steady increase in the order of 30.3%, 6.3% and 12.3% growth which indicates that the stiffness of the material will continue to increase and get more brittle after the earlier 43.8% decrease of material stiffness at 12 mAs of irradiation dose.

Figure 2 shows the tensile force–elongation curves of the tested samples. The curves described the level of brittleness and ductility of the composite material samples with regards to the amount of X-ray intensity exposure. For sample-A, the specimen elongated with the increased force level–up to certain value of 4324.9 N where the layer along with the reinforce fibre failure occurred. The curve is continuous until complete failure of the specimen took place as the outer layers of the laminate reached its peak. Similarly, sample-F produced a continuous curve just like sample-A, but, the peak test-value is 3314.9 N which is less comparatively to the former. The implication is that the latter sample experienced decrease in strength due to x-ray exposure. Furthermore, we observed that sample B, C and D which their X-ray treatment happened in between intensity values of sample A and F are all failed more than ones as shown in Figure 2. Their curves are not continuous which revealed that the material is really a composite material–and this time; their constituent materials experienced delamination which was resulted by main chain breakdown of the polymer. They failed differently due to increasing X-ray intensity impact. This is possible due to the two phenomenal: the intercross-linking and secession reaction that plays out as a result of X-ray photoelectrons emission on composite material that is in use [17]. However, the continuous curve of sample-A is an indication that the constituent materials were still bonded perfectly to each other as one material during sample-test. Similarly, sample-F continuous curve shows that all the constituent materials have been affected equally following the process of secession reaction completion; therefore, their failure happened simultaneously.

Figure 3a, b, c, d and e shows the line graphs of tensile properties versus X-rays intensity of the CFRP laminate. The following tensile properties: elongation, stress, force, Young's modulus and energy to break were considered for the evaluation of the material response to X-ray treatment. Among the results presented, it was discovered that elongation, stress, force and energy to break have the same graph line profile. Their graph lines pattern is zigzag which indicates that X-ray exposure influence to composite laminates cannot be effectively decided through tension test experiment [11, 12, 13, 14]. However, Young's modulus tensile property decided otherwise. It produced graph curve that demonstrated exactly how the CFRP laminate was affected by X-ray exposure. The sample-A without any exposure yielded at 2690.89 MPa followed by sample-B which was exposed to 6 mAs intensity of X-ray irradiation. The latter yielded at 2321.75 MPa and sample-C that received 12 mAs dose yielded at 1511.16 MPa which happen to be the lowest drop in the material strength. After this level of exposure, the material strength started to increase– samples-D yielded at 2169.46 MPa, sample-E yielded at 2316.05 MPa and sample-F yielded at 2641.77 MPa under 18 mAs, 24 mAs and 30 mAs of X-rays intensity respectively. This sudden increase in value shows that the material is getting more brittle and will continue until the material is completely degraded. Also, the observed tensile property increase and subsequent decrease with increasing X-ray intensity suggested that photo cross-linking and photo degradation phenomenon took place simultaneously during the X-ray treatment. At low doses of intensity, the tensile strength accelerated due to photo cross-linking of electrons resulted from combined reaction. But at higher intensity of X-ray irradiation, the photoelectrons emission which resulted in actual chain breakdown took place. Thus, the composite matrix experienced degradation which results in tensile property decrease with increase of X-ray treatment after a certain dose.

Table 2 shows the data sets for the ANOVA of the two method–numerical and experimental analysis of tensile young's modulus. The two methods were compared and their products reported in (Table 3). The computed t-value 4.51 was used to compare the critical t-value 2.57 for 5% level of significance and 5 degrees of freedom and it happened to be higher than the critical t-value [28]; therefore, the conclusion implies that the result is significant at the 5% level [27]. That is, also to say, the null hypothesis is rejected which suggests that both approaches are relevant in the investigation.

Figure 4 is a correlation graph for tensile young's modulus. It also shows how good the both approaches employed in investigating the material samples relate. The two curves in Figure 4 have the same response but with a little variation which was noted in the result of the fifth sample. The theoretical approach result decreased to the lowest at 1407.95 mAs in strength at the test of sample-E, which was treated at the X-ray intensity of 24 mAs before the final increase which was recorded with the last sample that has 30 mAs of exposure. Ordinarily, this fluctuation observed with the numerically determined results wouldn’t have been seen there; but, in the theory practice, the presence of Stress (δ) has
an influence over tensile young's modulus numerical calculation (equation 4). Though, Eisenreich and Cox [13] earlier had observed that strength values are found to be inconsistent in tensile tests investigation at cryogenic temperatures. This research thus, has given credence to their work in some aspects. However, experimental approach has proven to be more reliable while testing for tensile young's modulus particularly, especially when the CSMGF-even-concentration among samples is in doubt.

4. Conclusion

Tensile test is one of the dominating mechanical properties characterization procedures. Its application in the investigation of some of the mechanical behaviours of composite material (CSMFRP) laminate has raised some concerns to material engineering researchers, on the inconsistency in data values of tensile properties. One can easily deduce the following from the experiment conducted.

1. The major conclusion is that it is possible to measure tensile property of composite material at cryogenic temperature through experimental procedure directly without the problem of open-hole or computer aided simulation process. Tensile young's modulus is found to be

| S/No | Young's Modulus (MPa) | Numerical Method (M1) | Experiment Method (M 2) | Difference di = M2 - M1 |
|------|-----------------------|-----------------------|------------------------|------------------------|
| 1    | 2039.09               | 2690.89               | 651.80                 |
| 2    | 1760.72               | 2321.75               | 561.03                 |
| 3    | 1520.88               | 1511.16               | -9.72                  |
| 4    | 1566.07               | 2169.46               | 603.38                 |
| 5    | 1407.95               | 2316.05               | 908.09                 |
| 6    | 1995.23               | 2641.77               | 646.5                  |

Table 2. Comparative analysis for tensile Young's modulus results.

| Variable                  | Symbol | Value   |
|---------------------------|--------|---------|
| The average difference    | $d$    | 560.19  |
| Variance                  | $S_d$  | 92711.09|
| Standard deviation        | $S_d$  | 304.48  |
| t-statistic               | $t$    | 4.51    |

Table 3. Comparative analysis result.

**Figure 3.** Tensile properties versus X-rays intensity curves of the GFRP laminate: (a) elongation versus X-rays intensity, (b) energy to break versus X-rays intensity, (c) stress versus X-rays intensity, (d) force versus X-rays intensity, (e) Young's modulus versus X-rays intensity [Scilab 5.5.2].
consistent in their values, following X-rays exposure effect due to diverse intensity variation.

2. Scilab-numerical evaluation approach could only produce result values that are inconsistent in all the tensile properties test, including young's modulus. This is possible since the variables which constitute the tensile young's modulus model influenced the result values of the data obtained. Thus, the result of this investigation has given credence to the fact that tensile mechanical property cannot be trusted always, especially when precise test results are needed for composite material.

3. X-ray exposure of 12 mAs intensity to chopped strand fibre reinforced polymer laminate has proven to be a good recommendation for improvement of GFRP laminates quality. The experimental value at 12 mAs X-ray treatment produced the lowest tensile young's modulus value which represents high modulus of elasticity. In other words, the material is less brittle at that point.

Finally, this work has also helped to resolve the frustration that resulted from the factors indicated by Eisenreich and Cox [13]. Tensile young's modulus is a very reliable means of checking tensile mechanical property of a composite material, especially when performed experimentally. Therefore, tensile property test is still relevant in the test of composite materials at cryogenic temperature.

**Declarations**

**Author contribution statement**

Christopher O. Ndukwe: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Benjamin O. Ezurike: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Paul C. Okpala: Contributed reagents, materials, analysis tools or data; Wrote the paper.

**Funding statement**

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Data availability statement**

Data included in article supplementary material/referenced in article.

**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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