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# Analyzing the Tensile Strength of Carbon Fiber-Reinforced Epoxy Composites Using LabVIEW Virtual Instrument

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***Abstract:*** *Carbon fiber-reinforced polymer composites are widely used materials in the aircraft industry, automotive sector, marine applications, civil engineering, and daily consumer goods, due to their superior mechanical properties at a relatively low density compared to metallic materials. The studied composites are composed of an epoxy resin matrix in which three layers of carbon fiber fabric are embedded, oriented at 0 and 90 degrees. Carbon fiber-reinforced polymer composites were manufactured using the Vacuum Assisted Resin Transfer Molding technique. The tensile failure mechanism in carbon fiber-reinforced polymer composites is an extremely complex phenomenon influenced by numerous factors. This study aims to evaluate the mechanical behavior of carbon fiber-reinforced composites through tensile testing and to compare experimentally obtained results with those calculated using the mixture rule. Additionally, the behavior of the materials under tensile stress was analyzed using the digital image correlation method. Estimating mechanical properties based on the mixture rule is a common practice in the design phase of polymer composites. This study's novelty and originality lie in its anticipation of the tensile strength and modulus of elasticity of the studied composites. This anticipation was achieved using a virtual instrument developed in the LabVIEW graphical programming environment. The experimentally obtained results for the tensile characteristics of the studied materials are suitable for this type of composite. These results were compared with estimates derived from the mixture rule, and the absolute error was determined.*

***Keywords***: *carbon fiber reinforced composite, tensile strength, tensile modulus, image correlation*

## 1. Introduction

The current trend in the industry is to use lightweight and high-strength performance materials, with high fatigue and corrosion resistance, vibration damping, and noise attenuation characteristics, which are not always achievable with conventional metallic materials. A wide range of products in the aerospace industry (fuselage, wings, seats, flooring, engine fan) is made from carbon fiber-reinforced plastics, reducing aircraft weight and fuel consumption [1, 2]. Additionally, the European Union has set a target to reduce carbon emissions by 55% by 2030 [3]. In response, companies in the automotive sector are seeking solutions to reduce carbon dioxide emissions [4], showing significant interest in carbon composite parts to reduce automobiles' weight. Carbon fiber-reinforced polymer materials (CFRP) are used for auto components like doors, bumpers, and complex-shaped parts. However, the manufacturing time and high production costs limit their use for large-scale car production.

Composite materials allow for the creation of complex-shaped and large-sized products, with properties that can be designed and optimized by selecting suitable constituent materials and arranging fibers according to the load direction. For products used in complex applications, the mechanical properties of composites need to be experimentally tested, as their strength varies depending on the type and direction of the applied loads. Tensile, impact, and bending tests are recommended for investigation in such cases.

Composites are materials composed of a matrix in which reinforcing materials such as carbon, glass, aramid, Kevlar, natural fibers, etc., are embedded. Although each material retains its properties after

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mixing, the resulting composite has different mechanical characteristics compared to its individual components.

The mechanical properties of CFRP have been extensively studied in recent years [5-10]. The values of mechanical characteristics in literature vary due to numerous manufacturing factors. The mechanical response of carbon-reinforced polymer composites depends on factors such as composite manufacturing technology, volumetric fractions of constituent elements, fiber orientation concerning the load direction, interface between matrix and reinforcement, etc. The quality of the interface between fibers and matrix is a factor that hasn't been quantitatively determined, although its influence on tensile strength has been highlighted through qualitative rupture models [11]. A weak interface between matrix and carbon fibers results in reduced tensile strength and poor stress transfer between fiber and matrix. Recent studies have shown that the interface quality can be improved through various techniques: deposition of carbon nanotubes, electropolymerization, chemical vapor deposition, and electrophoretic deposition [12].

According to experimental results described in [13], a significant factor for composites is the stress-strain behavior of the matrix and reinforcement material. In the case of polymer composites with carbon fibers, the matrix is ductile while the fibers are brittle.

The overall structural performance of carbon fiber composites has been extensively studied and described in the literature. Tensile strength and modulus typically increase with increasing bulk density [14]. The tensile strength of composite laminates depends on the laminate orientation.

The tensile strength of polymer matrix composites laminated with carbon fibers can be estimated using the mixture rule. Although this topic has been extensively discussed in the literature, there is no clear evidence of precise adherence to the mechanical characteristic values calculated based on this rule. To quickly and accurately verify whether the material properties studied comply with this rule, an application was developed in the LabVIEW graphical programming environment.

Furthermore, the objective of this study is to comprehensively evaluate the mechanical behavior of CFRP through tensile testing, correlating experimentally obtained results with images captured by a digital system.

## 2. Materials and methods

### 2.1. Materials

The composites studied are a combination of layers of bidirectionally laid TR 30 S 3L carbon fibers within an IN2 epoxy resin matrix. CFRPs were manufactured using the Vacuum Assisted Resin Transfer Molding (VARTM) technique. Through this process, panels with dimensions of 300 mm x 400 mm were obtained, composed of a mixture of 60% fibers and 40% resin, with an almost negligible void content.

The IN2 epoxy resin used as a matrix was provided by EASY COMPOSITES. IN2 epoxy resin has very low viscosity, allowing it to be rapidly impregnated throughout the reinforcing material. Resin boasts excellent mechanical properties and is recommended for producing carbon fiber composites. Composites crafted from IN2 epoxy resin exhibit enhanced mechanical properties, reduced weight, and markedly superior performance compared to the individual constituent materials.

To ensure a proper cure, IN2 epoxy resin was mixed with AT30 SLOW hardener at a ratio of 100 parts of resin to 30 parts, per weight.

The main properties of IN2 Epoxy Infusion Resin, according to the manufacturer's technical sheet [15], are highlighted in Table 1.

**Table 1.** The properties of N2 Epoxy Infusion Resin [15]

| Properties | Values and Units |
|---|---|
| Commercial name | IN2 Epoxy Infusion Resin |
| Producer/Distributor | EASY COMPOSITES |
| Hardness 25°C | 86 – 90Shore D/15 |
| Maximum Tg | 75 – 81°C |
| Water absorption (24h RT) | 0.22 – 0.27% |
| Water absorption (2hr 100°C) | 0.95 – 1.00% |
| Flexural strength | 95 – 109MN/m² |

| | |
|---|---|
| Maximum strain | 4 – 6% |
| Strain at break | 7 – 9% |
| Flexural modulus | 2500 – 3100 MN/m² |
| Tensile strength | 67.0 – 75.0 MN/m² |
| Elongation at break | 5 – 7 % |
| Viscosity (20 °C) | 500 – 800 mPa.s. |
| Density (20 °C) | 1.08 – 1.18 g/cm³ |

### Carbon fiber

The reinforcement materials used for the experimentally studied laminate composite are made from TR 30 S 3L carbon fiber with a twill 2/2 weave, manufactured by Mitsubishi Chemical. The weaves are achieved through bidirectional alignment of the fibers at 0 and 90 degrees to each other.

The properties of the carbon fiber type TR 30 S 3L, according to the manufacturer's technical sheet [16], are presented in Table 2.

**Table 2.** The properties of carbon fibers [16]

| Properties | Values and Units |
|---|---|
| Commercial name | TR 30 S 3L Carbon fiber |
| Producer/Distributor | D Mitsubishi Chemical |
| Number of filaments | 3 |
| Filament diameter | 7 μm |
| Yield | 200 mg/m |
| Tensile strength | 4.12 GPa |
| Tensile Modulus | 235 GPa |
| Elongation | 1.8% |
| Density | 1.79 g/cm³ |

As described by the manufacturer in the technical datasheet, Carbon fibers type TR 30 S 3L exhibit high strength, high rigidity, high modulus, and low weight. Due to these superior characteristics compared to other types of reinforcement materials, carbon fiber tow finds applications across a wide range of industries, including the aerospace, automotive, and marine sectors, among others.

### 2.2. Preparation of Carbon fiber-reinforced epoxy composites

The studied composites were manufactured using the Vacuum Assisted Resin Transfer Molding process with a pressure of 1 bar and a temperature of 24°C.

The reinforcement material in the form of a 0/90 weave was laid in three layers within a metallic panel-type mold, after which the resin was infused under a vacuum.

The characteristics of the composite material studied are presented in Table 3.

**Table 3.** Characteristics of the composite material

| Properties | Values and Units |
|---|---|
| Reinforcement Material | TR 30 S 3 L carbon fiber |
| Matrix | IN2 Epoxy Infusion Resin |
| Weave | 2/2 Twill |
| Weave Weight | 200g/m² |
| Weave Yarn Density | 3K |
| Consolidated Thickness per Layer | ~0.28mm |
| Number of Weave Layers | 3 |
| Weave Orientation | 0°-90° |
| Hardener Type | AT30 SLOW |
| Casting Process | VARTM (1bar) |
| Curing Cycle | 24°C/24h |

Before the samples were taken for testing, the composites were allowed to be cured at a temperature of 24°C for 24 h. The extraction of specimens with shapes and dimensions conforming to the standard was accomplished using a Computer Numerical Control (CNC) machine through a water jet cutting process.

The ASTM D638 standard was utilized to establish the dimensions and shapes of the tensile test specimens. The dimensions specified by the ASTM D638 standard for the test specimens are as follows: a thickness of 2 mm, an overall length of 165 mm, a width of 13 mm at the neck, and 19 mm at each end [17, 18]. The dimensions and shapes of the tensile test specimens are illustrated in Figure 1.

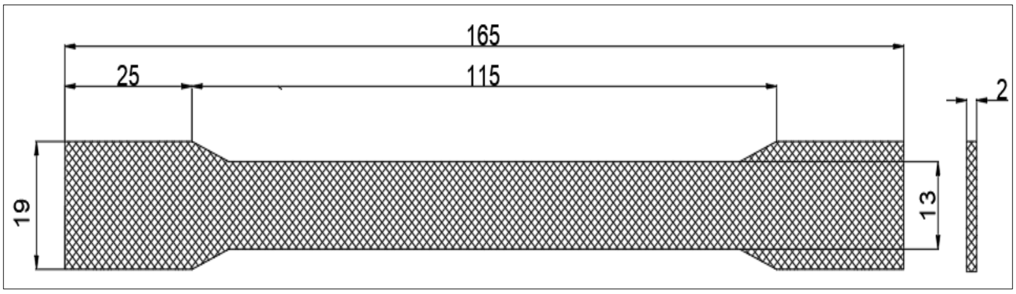


**Figure 1.** The dimensions and shapes of the tensile test specimen

### 2.3. Methods

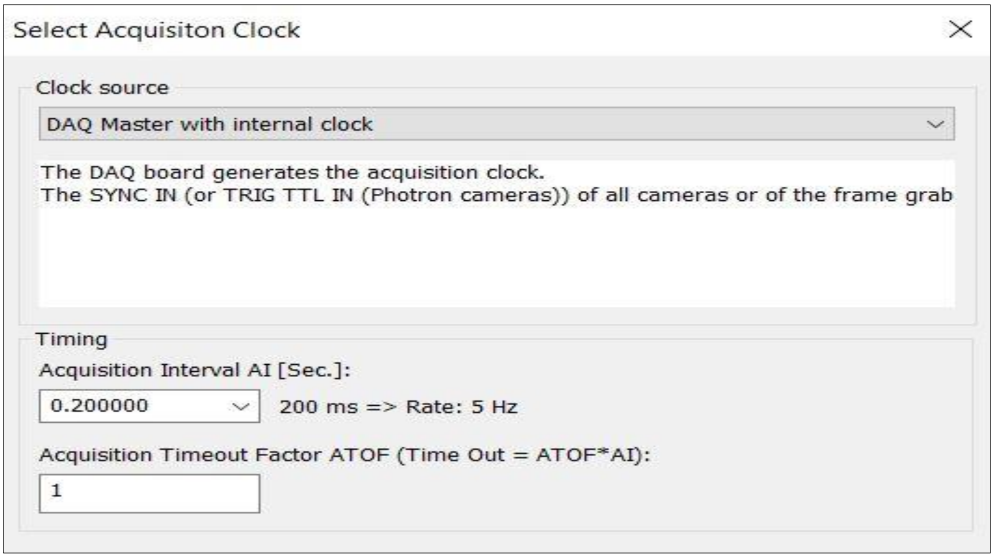
Tensile tests were conducted in accordance with ASTM D638 standard [17].

The aluminum reinforcements adhered to the ends of the samples to prevent slippage during the experimental tensile trials. The experimental tests were carried out at the Materials Strength Laboratory within the University Politehnica of Bucharest. The tensile tests of the samples were performed using an INSTRON 8872 system for static and dynamic axial testing, with a maximum load capacity of 25 kN. The equipment utilized is equipped with two columns to ensure increased rigidity during material testing. The distance between the columns is 455 mm, and the maximum distance between the lower and upper grips is 820 mm. Moreover, the system features a drive cylinder and a force cell positioned at the top. The specimens were securely held in place using a hydraulic gripping system. Tensile loading of the samples was applied at a constant speed of 2 mm/min.

The coefficient of transverse contraction (Poisson's ratio) was determined during tensile testing. Additionally, through the adopted experimental method, digital image correlation (DIC) was used to correlate images and obtain the Poisson's ratio for the tensile-tested samples, correlated with measurements obtained from the load cell of the INSTRON 8872 hydraulic testing system.

Digital image correlation (DIC) is a non-contact method used by numerous researchers to study the mechanical characteristics of materials. This method is recommended for measuring stress over a large surface area, replacing strain gauges for measuring deformation across the entire surface. This method enabled the analysis of micro-scale fracture mechanisms and the observation of details regarding the appearance and propagation of fractures in constituent elements of the composite. With the help of DIC, localized deformations on the measurement surface were verified during experimental tests, and the stress-strain evolution of the experimentally researched composite material was studied.

Digital scanning during the tests was performed using an ISTRA 4D digital image correlation system. The system is equipped with a 5 Mpx USB3.0 Camera and an SK lens for the Q-400 camera. The five tensile test specimens were placed under the microscope's SK lens, which has a focal length of 50 mm and a sensor size of 4/3” C.C.D. Before testing, the specimen surfaces were sprayed with white particles to cover the entire surface, allowing for optical tracking of point movement (in contrast to the black color of the composite). The image correlation method involved setting some parameters for the ISTRA 4D digital system, as configured in Figure 2.



Clock source
DAQ Master with internal clock
The DAQ board generates the acquisition clock.
The SYNC IN (or TRIG TTL IN (Photron cameras)) of all cameras or of the frame grab

Timing
Acquisition Interval AI [Sec.]: 0.200000
200 ms => Rate: 5 Hz
Acquisition Timeout Factor ATOF (Time Out = ATOF*AI): 1

**Figure 2**. Setting up the parameters for data acquisition

Setting up the parameters for data acquisition has involved the following steps:

- *Frame Rate and Interval:* The frame acquisition was configured to capture images at a frequency of 5 Hz, with an interval of 200 ms between consecutive frames. This setting allowed for capturing the deformation process with a high temporal resolution.
- *Camera and Lens Configuration:* The ISTRA 4D system was equipped with a high-resolution 5 Mpx USB3.0 Camera and an SK lens specifically designed for the Q-400 camera. The camera and lens configuration ensures clear and detailed images for accurate analysis.
- *Specimen Dimensions:* The dimensions of the test specimens were entered as input into the ISTRA 4D software. This information is crucial for accurately interpreting the deformation data and associating them with the actual dimensions of the specimens.
- *Illumination System:* To ensure uniform lighting across the sample surfaces, a cold illumination system known as HILIS was employed. This illumination setup minimizes shadows and variations in lighting, ensuring consistent image quality.
- *Contrast Enhancement:* Prior to testing, the specimen surfaces were coated with white particles. This contrast enhancement technique allows for better optical tracking of point movement by creating a distinct visual contrast against the black color of the composite material.

By meticulously configuring these parameters, the data acquisition process was optimized to capture high-quality images of the deformation behavior of the specimens during experimental tests. The combination of accurate image correlation and proper parameter setup facilitated the analysis of material characteristics and deformation patterns with enhanced precision.

After configuring the data acquisition parameters within the digital image correlation system, the evolution of the stress-strain behavior of the composite material was analyzed.

## 3. Results and discussions

Carbon fiber-reinforced polymer composite samples were subjected to a tensile load in order to determine their primary mechanical characteristics. Tensile strength, tensile modulus, elongation, and Poisson's ratio were obtained from this testing.

The results of the tensile test are presented in Table 4.

**Table 4**. Tensile test results

| Samples | Tensile Modulus [MPa] | Ultimate Tensile Strength [MPa] | Poisson’s ratio |
|---|---|---|---|
| P1 | 29604.1 | 330.1 | 0.06 |
| P2 | 29686.8 | 331.5 | 0.07 |
| P3 | 30409.1 | 316.9 | 0.05 |
| P4 | 30125.1 | 301.8 | 0.06 |
| P5 | 28941 | 235.5 | 0.08 |
| Median value | 29686.8 | 316.9 | 0.06 |
| Standard deviation | 560.1 | 39.6 | 0.01 |
| Coefficient of variation | 1.8 | 12.5 | 19.003 |

According to the results presented in Table 4, the average value of Young's modulus for the studied composite materials is 29686.8 MPa within the proportional region of the stress-strain curve (σ - ε), with a coefficient of variation of 1.8%. Meanwhile, Poisson's ratio has an average value of 0.06, with an approximate variation of 19%.

The result values for the five specimens exhibit a low level of dispersion, with all stress-strain curves showing a similar progression. Figure 3 illustrates the stress-strain curves (σ - ε) for the five tested samples, P1-P5.

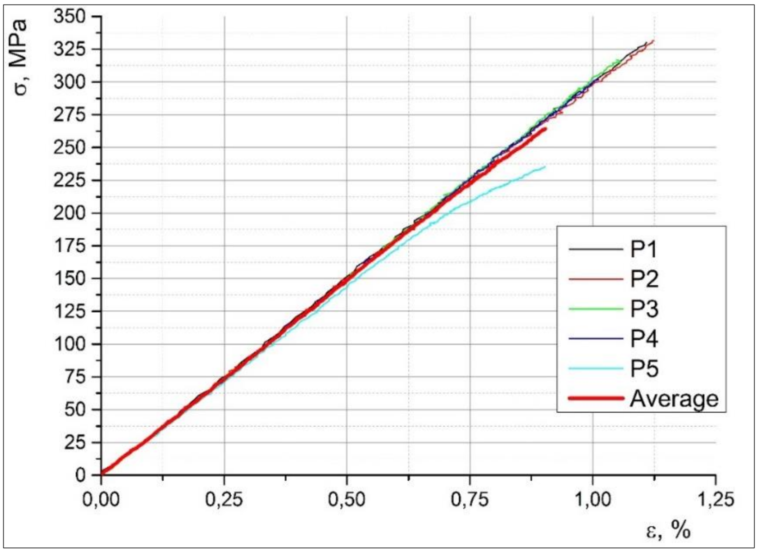


**Figure 3.** The stress-strain diagram

As observed from the stress-strain curves of the five tested specimens, the maximum deformation of composites reached an approximate value of 1.13%. The linear elastic behavior in the stress-strain curves for all five tensile test samples remained consistent until their eventual fracture. This behavior can be attributed to the high strength of the laminate composites with bidirectional carbon fiber weaving.

The results of the tensile tests revealed that the rupture of the bidirectional carbon fiber composite began with the fracturing of the carbon fibers, leading to plastic deformation. The fracture of the composite didn't occur rapidly because not all fibers fractured simultaneously. This behavior is influenced by the notable variations in fracture toughness among brittle fiber materials. The region of brittle fracture persisted as long as the matrix remained intact, and the fibers continued to bear the load while the matrix experienced plastic deformation. Only a very small fraction of the applied load was supported by the matrix phase.

The images illustrating the fractured composite specimens after the tensile tests are displayed in Figure 4.

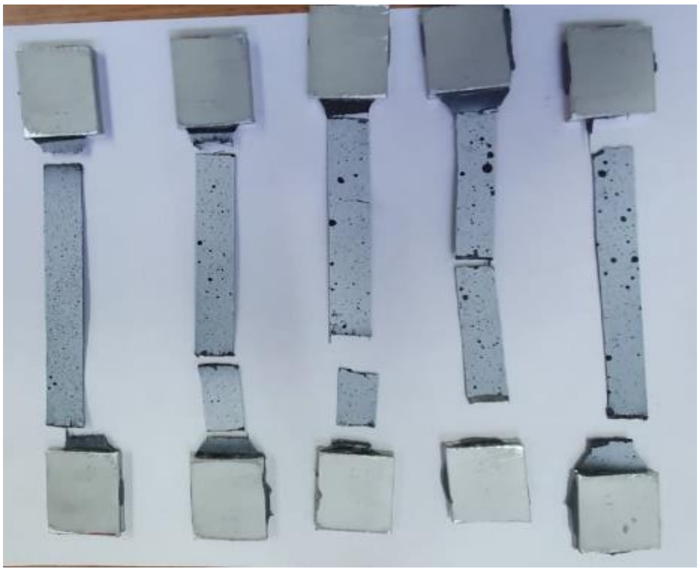


**Figure 4.** Fractured composite specimens after tensile testing

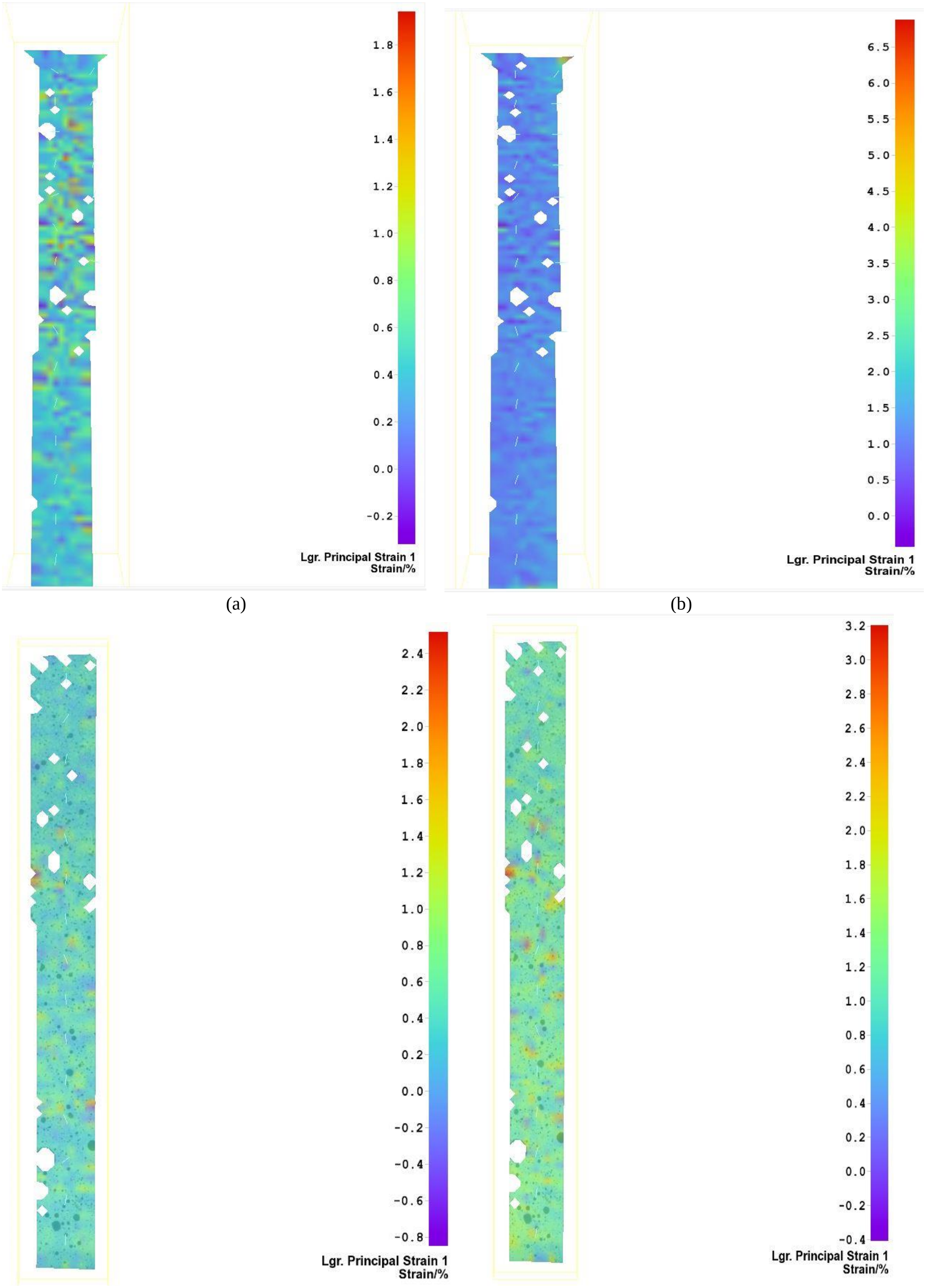
The fracture morphology is approximately similar in all five specimens. Minimal occurrences of delamination or fiber pullout were observed in the cross-sectional areas of the samples. The resin is tightly bonded to the fibers, no fiber bundles are apparent, and the rupture occurs within the matrix.

The microscopic mechanical behavior of the composite materials was analyzed based on the images obtained using the digital image correlation system.

During the tensile testing, the displacement of carbon fabric exhibited a diagonal pattern, characteristic of twill 2/2 weaving behavior under tensile stress. Uncolored points in the images represent areas that couldn't be tracked by the data analysis software to detect fiber displacement. Small cracks in the IN2 epoxy resin matrix were observed in certain sections of the specimens.

From the diagrams obtained, it was observed that the composite material undergoes elastic deformation over nearly the entire curve, followed by a very small region of linear plastic behavior. With an elasticity modulus coefficient of variation of only 1.88%, all specimens exhibited similar mechanical behavior across their lengths. The average value of Ultimate Tensile Strength was 316.94 MPa, with a coefficient of variation of only 12.52%. The fracture of the specimens occurred in the transition section of cross-sectional dimensions, through simultaneous rupture of the matrix and fibers, representing a fracture mode specific to carbon fiber-reinforced composites. This fracture mode in the reduced section of the specimens is in accordance with the tensile testing standard.

Figure 5 presents frames from the tensile test for samples P1 and P2, captured at different time intervals.



(a) (b) (c) (d)

**Figure 5.** The principal strain obtained for D.I.C. evaluated tensile test specimens: (a) and (b) - P1 specimen; (c) and (d) - P2 specimen

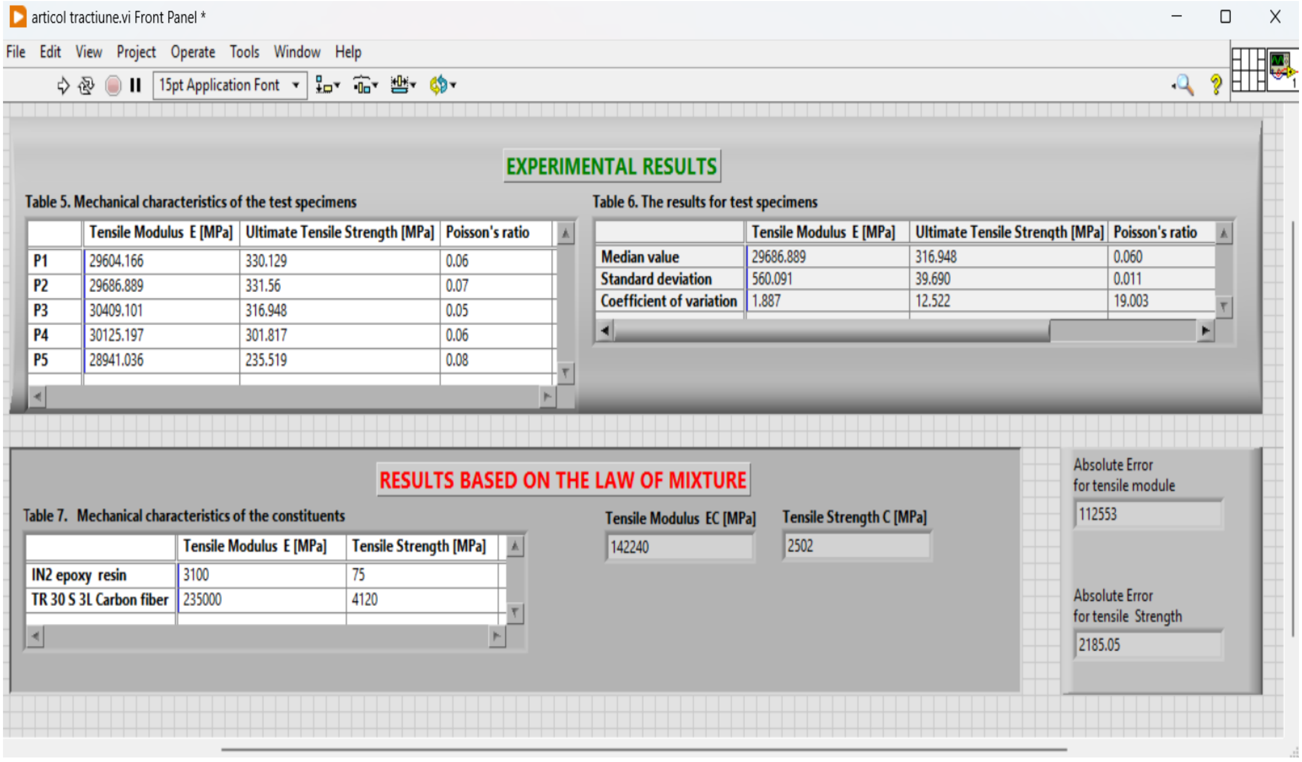
## The estimation of mechanical characteristics of Carbon Fiber-Reinforced Polymer

The estimation of mechanical characteristics of CFRP based on the rule of mixtures involves predicting the composite's properties by considering the properties of its individual constituents. The rule of mixtures considers the volume fraction of each component (fiber and matrix) in the composite and calculates the values of the properties.

For the estimation of the mechanical characteristics of CFRP, a virtual instrument was developed in the LabVIEW graphical programming environment. The virtual instrument calculates the median value, standard deviation, and coefficient of variation for the five tested specimens. It also calculates and displays the tensile strength and Young's modulus based on the formulas provided by the rule of mixtures, along with the absolute error for these values.

Input data was entered through control elements (Table 5 and Table 7) for the specimens subjected to tensile testing, in the application's front panel. When the virtual instrument is run, the calculated results are displayed in indicator elements: Table 6, Tensile modulus EC, Tensile Strength C, and Absolute Error.

Figure 6 illustrates the front panel of the LabVIEW virtual instrument that was developed for this study.



EXPERIMENTAL RESULTS

Table 5. Mechanical characteristics of the test specimens

| | Tensile Modulus E [MPa] | Ultimate Tensile Strength [MPa] | Poisson's ratio |
|---|---|---|---|
| P1 | 29604.166 | 330.129 | 0.06 |
| P2 | 29686.889 | 331.56 | 0.07 |
| P3 | 30409.101 | 316.948 | 0.05 |
| P4 | 30125.197 | 301.817 | 0.06 |
| P5 | 28941.036 | 235.519 | 0.08 |

Table 6. The results for test specimens

| | Tensile Modulus E [MPa] | Ultimate Tensile Strength [MPa] | Poisson's ratio |
|---|---|---|---|
| Median value | 29686.889 | 316.948 | 0.060 |
| Standard deviation | 560.091 | 39.690 | 0.011 |
| Coefficient of variation | 1.887 | 12.522 | 19.003 |

RESULTS BASED ON THE LAW OF MIXTURE

Table 7. Mechanical characteristics of the constituents

| | Tensile Modulus E [MPa] | Tensile Strength [MPa] |
|---|---|---|
| IN2 epoxy resin | 3100 | 75 |
| TR 30 S 3L Carbon fiber | 235000 | 4120 |

Tensile Modulus EC [MPa]
142240

Tensile Strength C [MPa]
2502

Absolute Error for tensile module
112553

Absolute Error for tensile Strength
2185.05

**Figure 6**. Front Panel of the virtual instrument

The programming algorithm used was based on the calculation formulas specified in the rule of mixtures. The estimation of tensile strength and Young's modulus for CFRP, based on the rule of mixtures, involves incorporating the characteristics of each constituent material into the calculation formulas:

$$\sigma_C = \sigma_F * V_F + \sigma_M * V_M \tag{1}$$

where:

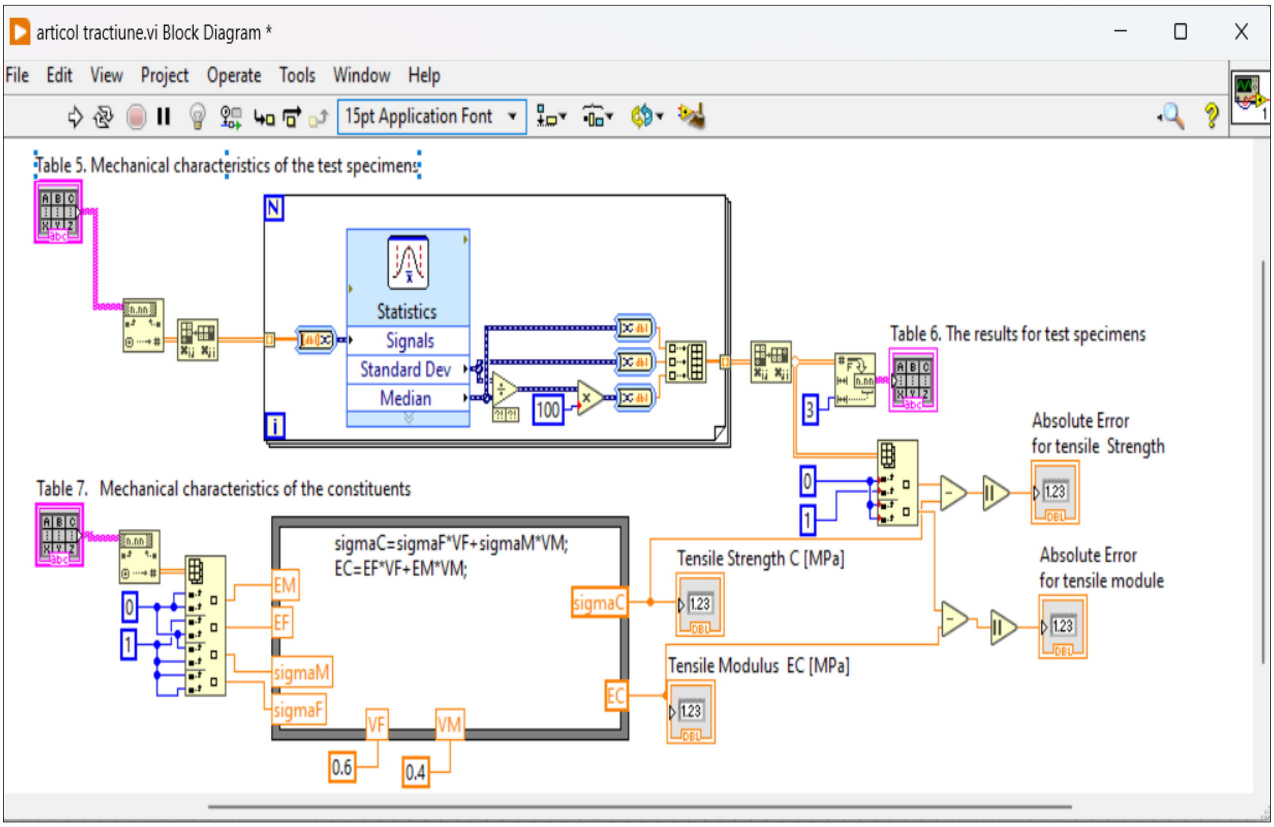
$\sigma_C$ - represents the tensile strength of the composite material.
$V_F$ - is the volume fraction of fibers.
$V_M$ - is the volume fraction of the matrix.
$\sigma_F$ - is the tensile strength of the fiber.
$\sigma_M$ - is the tensile strength of the matrix.

$$E_C = E_F * V_F + E_M * V_M \tag{2}$$

where:

$E_C$ - represents the tensile modulus of the composite material.
$E_F$ - is the tensile modulus of the fiber.
$E_M$ - is the tensile modulus of the matrix.

In Figure 7, the diagram of the virtual instrument is presented, where the programming algorithm based on the above formulas has been implemented.



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sigmaC=sigmaF*VF+sigmaM*VM;
EC=EF*VF+EM*VM;
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**Figure 7**. Virtual instrument diagram

The experimentally obtained average tensile strength value (316.948 MPa) is close to the values recommended in specialized literature [17-19], but significantly different from the value determined based on the rule of mixtures (2502 MPa), resulting in an absolute error of 2185.05 MPa. Similarly, the calculated modulus of elasticity based on the rule of mixtures (142240 MPa) significantly differs from the experimentally determined average modulus of elasticity (29686.889 MPa), with an absolute error of 112553 MPa. These large errors are because relationships based on the rule of mixtures do not account for the influencing factors of composite material properties; they rely on simplifying assumptions that lead to significantly different values from the actual properties of the composite materials.

Therefore, it is recommended that for important applications of composites, their mechanical characteristics should be determined experimentally, based on the operational stresses they will undergo. This approach considers the specific properties and behaviors of the composite materials, ensuring more accurate and reliable results for practical applications.

## 4. Conclusions

This article focused on studying the tensile mechanical properties of carbon fiber-reinforced material. The mechanical characteristics of the studied composites vary within broad ranges, influenced by numerous factors. The experimentally obtained results make a significant contribution to the study of polymer composites, both at the microscopic and macroscopic levels, providing a better understanding of the mechanical behavior of CFRP under tensile loads.

Tensile strength and elastic modulus for CFRP were calculated using the rule of mixtures with the LabVIEW virtual instrument and were compared to the experimentally determined values. The large absolute errors suggest that the rule of mixtures can be used for initial approximations in composite material design. However, for critical applications, the mechanical characteristics of CFRP composites should be determined experimentally, considering the influence of all factors. Real properties can significantly vary based on multiple factors, including composite material manufacturing techniques.

The virtual instrument developed in the LabVIEW graphical programming environment could be used to estimate any property of composite materials, provided that relevant data about the composites under analysis are available. The programming algorithm proposed in this work can serve as a developmental model for creating a program that estimates the desired properties of composite materials based on input data.

In conclusion, this research has made a significant contribution to understanding the fracture mechanism and mechanical properties of laminated polymer composites with carbon fiber reinforcement. The application of the rule of mixtures should be used with caution when evaluating these materials.

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