# Specific Energy Absorption Evaluation on GFRP Laminate Plate by Optical, Thermographic and Tomographic Analysis

# *"Specific Energy Absorption evaluation on GFRP laminate plate by Optical, Thermographic and Tomographic analysis"*

E. Virgillito, A. G. Airale, A. Ferraris, L. Sisca, M. Carello

Department of Mechanical and Aerospace Engineering - Politecnico di Torino

C.so Duca degli Abruzzi 24, 10129 Torino, Italy

## Abstract:

A large number of studies have been carried out over the years on glass fiber composite materials in order to analyze their impact behavior. An analysis of the drop impact behavior of GFRP laminated plate (Epoxy resin matrix reinforced with E-Glass Twill woven) subjected to various impact speeds in low impact velocity or LVI[1] has been performed. Then the SEA[2] of the material was calculated, using different non-destructive measurement techniques to analyze the surfaces of rupture. The three methods used are: Optical Analysis, IR-Thermography and X-ray Computed.

## Introduction

Using advanced composite material technology, automotive engineers can reach a new level of light-weight design for vehicles. Some academic research performed in recent years [1] [2] have shown a first attempt also for industrial level production [3]. In order to have a deeper understanding of composite material characteristics, impact resistance is one of the most important aspects that need to be studied. From this point of view, polymer matrix composite materials have been studies over the years by material engineers: most of these papers are focused on the material's characterization and identifying experimental parameters that affect the impact behavior of materials. Belingardi [4] has studied the influence of number of layer, stacking sequence and impact velocities and found a reliable way to describe the saturation energy of GFRP specimens. Other structural research for impact behavior of CFRP composite, such tubular specimens are carried out by Jacob [5] e Kilic [6] for SEA. Quaresimin [7] correlates the absorption of energy with the main parameters of the laminates using non-destructive techniques such as X-ray radiography, analysis through ultrasound and optical microscopy, however, most of the studies with NDEs are based on Thermography. Meola [8] carried out transmission tests with heating lamp for transparent/semi-transparent specimens, which is placed facing the back side of the specimen. A thermal camera was placed in front of a specimen and facing the non-heated surface to obtain the heat transmission through the sample. Another test is done for the same specimen by using normal camera to detect the visible light transparency. Comparison between the two tests gives the information about the damaged area. Colombo [9] analyzed the surface temperature by infrared thermography in order to detect the damage, which could lead to delamination, debonding at fiber-matrix interface, fiber breakage, matrix cracking or crazing, etc. [10] [11] [12]. Vergani [13] used thermographic analysis to correlate the surface temperature of the specimens with the amount of damage absorbed by the material. Alemi-Ardakani [14] was one of the first researchers analyzing the impact damage by using a Micro-tomographic technique, which can rebuild a virtual internal structure model of the material.

[1] LOW VELOCITY IMPACT

[2] SPECIFIC ENERGY ABSORBTION

Leonard [15] improved the experiment to investigate individual layers of material, which allows the researchers to understand the delamination after impact.

The main goal of this study is to compare several analysis methods for the material damage, to evaluate the best method that determines specific energy absorption for epoxy resin reinforced with glass fibers E-Glass (GFRP). In the beginning, In order to evaluate the energy absorption, the mechanical impact behavior of the samples were tested with different impact speeds. It is necessary to detect for possible presence of the strain rate effect in the material, such as the ability of the chosen material to deform in a different way for different impact velocities. The energy absorption coefficient of the material is a parameter that is normally evaluated on tubular samples in industrial applications. This is because the actual volume of work is easy to determine for the simple geometry, leading to a reliable result. However, experimental tests on tubes are expensive, requiring special equipment and complex post-processing analysis [5] [16], and limited only for tubular shape components. We used a different approach with planer specimens to obtain the SEA with simpler method, which costs less money and time. Different methodologies were chosen to evaluate the damaged surface, in order to calculate the effective volume for energy absorption of the specimen. Since GFRP is semi-transparent for visible light, "optical method" was done in the beginning. By using halogen lights, it is possible to obtain the area of damaged zone, which is used later to compute the effective volume for energy absorption. Then, an "Infrared Thermography method" was used to obtain the damaged area by exploiting the thermal conductivity of the heated material. The last analysis performed is " X-ray tomography method", which allows to create a detailed 3D model of the damaged specimens. By using this method, it was possible to obtain directly the effective volume for energy absorption. The results obtained are very different from those found in bibliography [5] because the different specimen geometry leads to inevitably different mechanisms of damage in the material. The later 2 method can also be applied to non-transparent materials.

## Materials e Test machine

The studied material is epoxy resin IMP503 reinforced with glass fiber pre-preg E-glass Twill 2x2 (194 g/m$^2$) produced via autoclave vacuum bag with thickness of 2 mm. All specimen are 100mmx100mm respecting to technical standard [17] and other common practices [4]. Since the material is transparent to light, it is possible to use optical method to study energy absorption, which also allows for obtain delamination and other fracture mechanisms. This method is validated by numerous articles [18]. Two tests with impact speed of 1.5 and 6 m/s were performed, so the strain-rate effects on the materials was evaluated. In order to compare the tests at different speeds, it was necessary to set similar amount of energy for each test by varying the mass acting on the Indenter and taking into account the limitations of the test equipment. The impact tests were performed using standard ASTM D7136 [17], which define the standard for free-fall drop dart testing for composite materials. To test the specimens, Instron Ceast 9350 was used (Figure 2). The machine is an impact tests instrument designed to provide energy from 0.59 to 757 J, drop height from 0.03 to 29.4 m (emulated), impact velocities from 0.77 a 24 m/s and a drop mass from 5.0 to 70.0 kg. The dart assembly is composed of a several steel plates with a spherical tip of 16.8 mm diameter. Impact vertical speed is then evaluated from the Δ t measured by passing 2 optical sensors. The calculation of the exact velocity need to be performed, in order not to overestimate the transition velocity of the impacting mass. The potential energy is considered without friction loss. The specimens are plates completely constrained on a circular hole of 76 mm in diameter by the clamping fixtures and tests were performed with an anti-rebound device. For the measurements, structure designed and built by our research group was used in order to standardize the acquisition of images from both thermal and optical cameras. It allows to fixed the light source and to vary the distances between source-specimen, the specimen-camera and their height. The following images shows the structure during thermal and optical analysis (Figure 1).


*Figure 1: Test Equamente*

*Figure 2: Instron CEAST 9350*

## Experimental Tests

Data shows below in Table 1 have been filtered because the rapid variation of the kinematic energy excites vibrations, which depends on the stiffness and mass of both the specimen and the impactor. The acquisition rate was 1 MHz, which is appropriate for sufficient number of sampled points for a phenomenon normally lasts less than 100 milliseconds. E-Glass Epoxy (iBB) specimens are tested with impact speeds of 1.5m/s and 6 m/s, and their curves Energy-Displacement and Force-Displacement are shown in Figure 4 and Figure 5. It could be seen that specimens are more brittle at lower impact speeds.

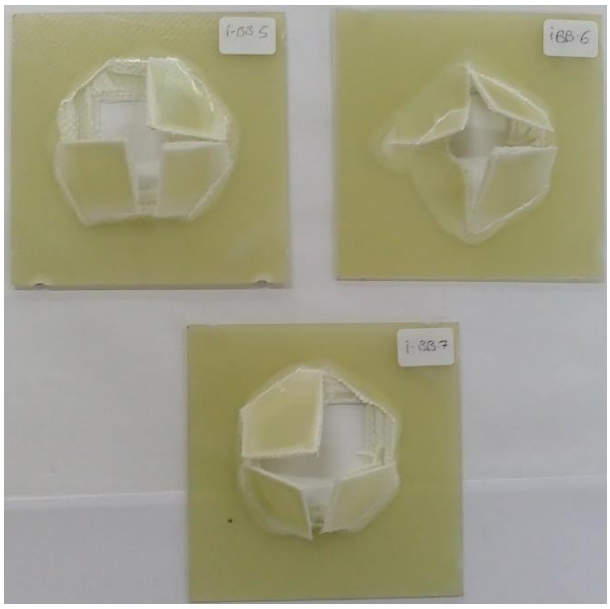


*Figure 3: iBB 1.5 m/s*

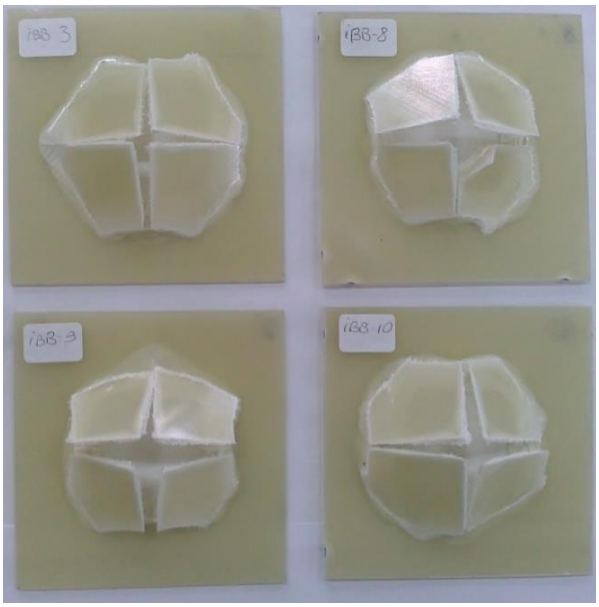


*Figure 4: iBB 6 m/s*

*Table I: Energy absorption*

| LVI E-Glass EP 0-90 | | | | | |
|---|---|---|---|---|---|
| **1.5 m/s** | **Specimen 1** | **Specimen 2** | **Specimen 3** | **Media** | **dev. Standard** |
| ***Absorbed Energy [J]*** | 24.27 | 26.42 | 25.34 | 25.34 | 1.08 |
| ***Maximum Force [kN]*** | 1.77 | 1.79 | 1.77 | 1.78 | 0.01 |
| **6 m/s** | **Specimen 4** | **Specimen 5** | **Specimen 6** | **Media** | **dev. Standard** |
| ***Absorbed Energy [J]*** | 31.85 | 30.62 | 29.50 | 30.65 | 1.17 |
| ***Maximum Force [kN]*** | 1.57 | 1.59 | 1.49 | 1.55 | 0.05 |

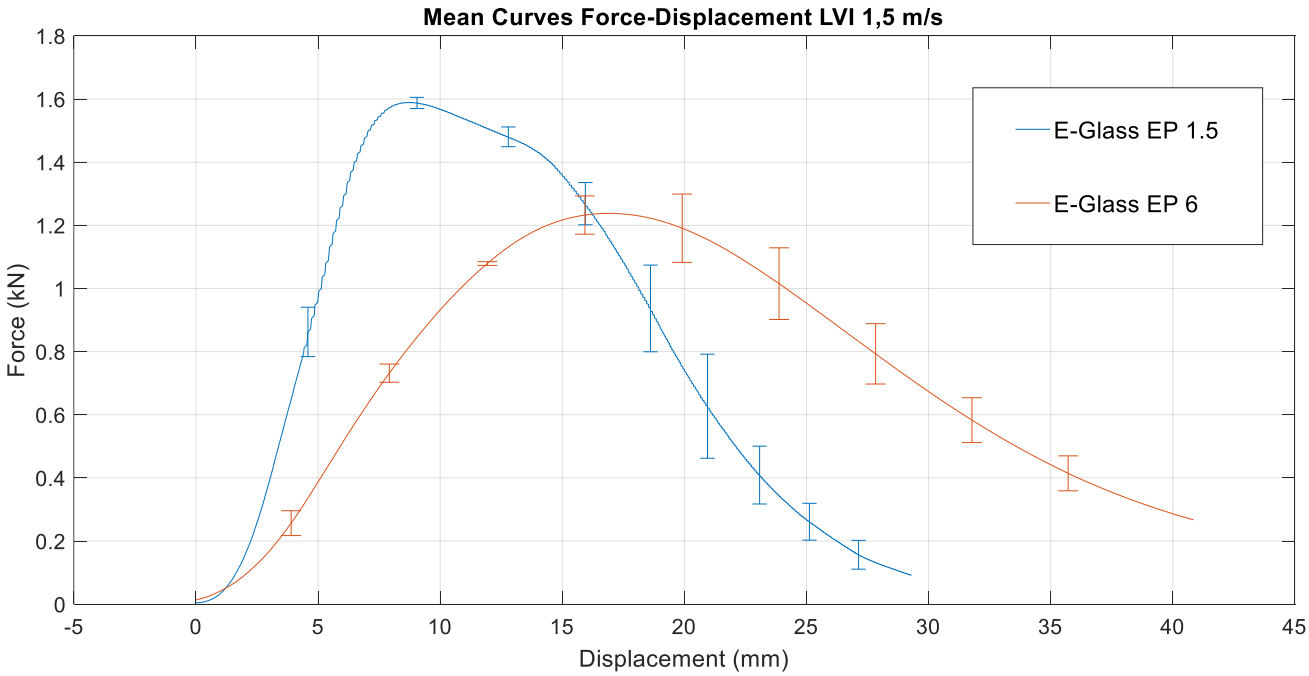


*Figure 4: Force-Displacement mean curve*

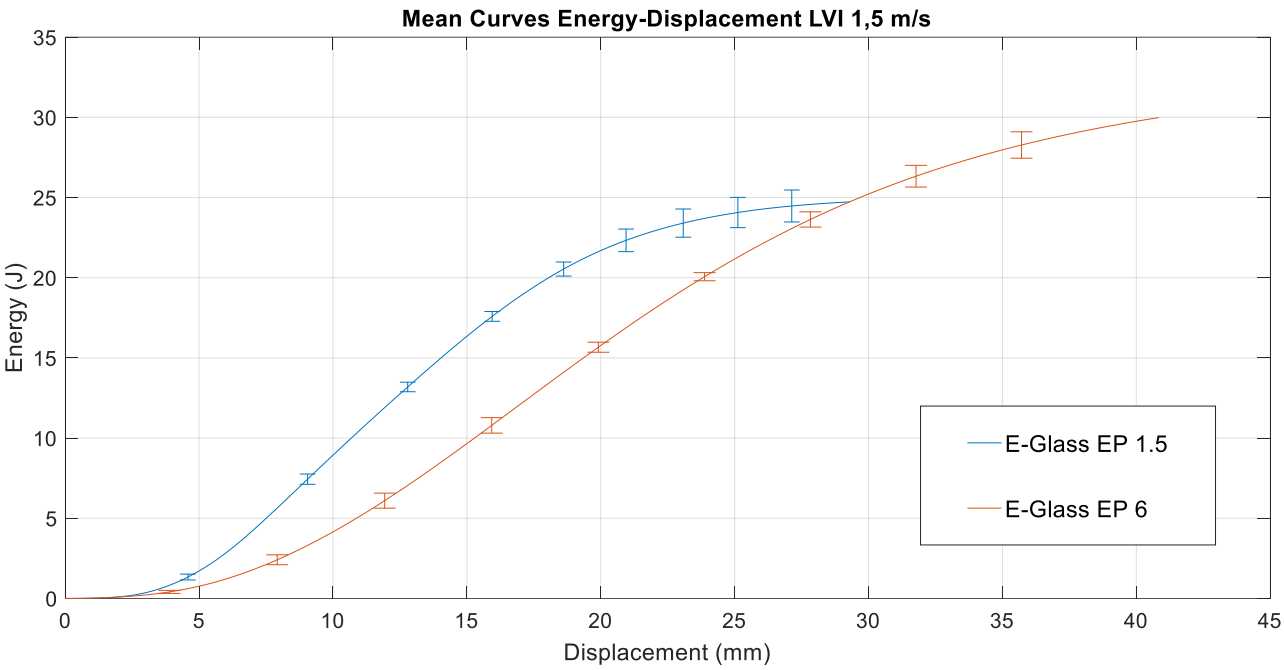


*Figure 5: Energy-Displacement mean curve*

## Specific energy absorption

"SEA" stands for the "specific energy absorption" of a material, which shows the energy absorption per unit mass (kJ/kg). It was difficult to identify a widely-used method for its measurement because it is not a standardized coefficient.

The mass of material in effected zone is commonly calculated by multiplying the effective volume and its density, which is obtained through the following formula:

$$\rho_c = \frac{1}{\left(w_f/\rho_f\right) + \left(w_m/\rho_m\right)}$$

*Equation 1; Theoretical density of a composite material*

Where: $\rho_c$ = composite density $w_m$ = weight percentage of matrix $\rho_m$ = matrix density

$w_f$ = weight percentage of fiber $\rho_f$ = fiber density

In our case $\rho_f$ = 2.57 $kg/m^3$, $\rho_m$ = 1.1 $kg/m^3$, $w_f$ = 0.667 and $w_m$ = 1 - $w_f$= 0.333 (all data are provided by material datasheets), $\rho_c$ = 1.78 $kg/m^3$ is calculated. After analysis the result, this method is proved unreliable for this application. The biggest issue is that the defects of productions (present in the very nature of the production process and cannot be avoid) had heavily influenced the characteristics of the material, changing the density as it is easy to note from Figure in the red circle (white dots have smaller density, where cavity is present). In the end the mass was calculated corresponding to the effective volume obtained by image correlation with knowing the initial mass of the specimen before the test.

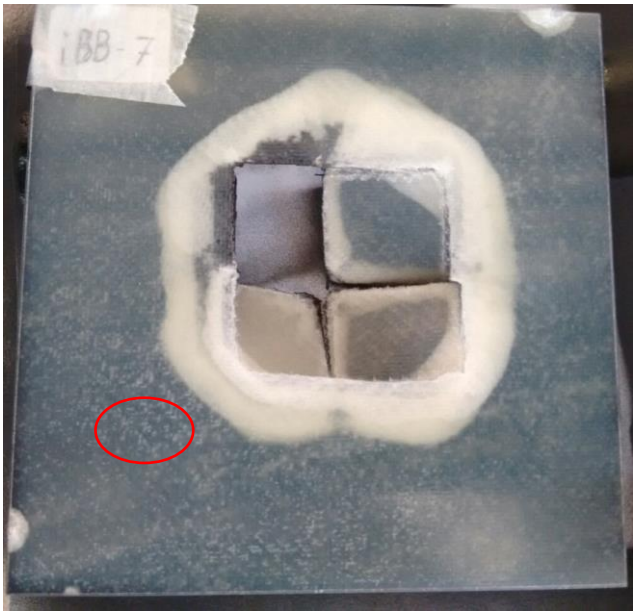


*Figure 7: Micro-porosity inside a specimen*

## Optical method

A specimen was placed between a halogen lamp and a camera to evaluate the impact area using image correlation tools, which further on transformed to the effective volume for energy absorption. This type of analysis is very simple but came with disadvantages. First it can only be applied to transparent specimens. Second the effective volume is obtained from 2D images, which needs to assume that the material damage is constant along the thickness of the specimen. The optical method is often used [18] for measuring area, but it can generate errors as much as 21% according to our experience, so does the calculated effective volume since it is obtained based on optical measured area. SEA of GFRP specimens obtained by optical method is shown in Table 1:

*Table 1 : Optical SEA*

| Optical method | | |
|---|---|---|
| **1,5 m/s (Specimen 1)** | | |
| **Effective Volume [cm$^3$]** | **Absorbed Energy [kJ]** | **Specific Energy Absorption [kJ/kg]** |
| 6.59 | 0.024 | 2.1 |
| **6 m/s (Specimen 4)** | | |
| **Effective Volume [cm$^3$]** | **Absorbed Energy [kJ]** | **Specific Energy Absorption [kJ/kg]** |
| 6.76 | 0.032 | 2.6 |

## Thermographic method

In this case specimens were interposed between a heat source (the same halogen lamp used in optical measurement) and an IRtech® Thermographic camera XT (Similarly to Meola [8]). The specimen is heated by the lamp and the IR camera measured the heat transmission through the specimen. A comparison between the results obtained by thermal graphic method and optical method has been performed.

Since delaminated area has interspace between the layers, transmission of heat is differently than the non-damaged part, which can be observed by using IR camera. The Thermal graphic method provides more detailed information for failure phenomenon than the optical method. Through software TImage®, it is possible to create a map of points (image correlation), where each pixel and has an associated temperature. Comparing all the frames taken during the measurement, a temperature different between the first frame to the last frame can be observed with a value at least $\Delta T > 2°$ C. The results were obtained from 2D images of the surface of the specimens, and same assumption of constant damage along the is made to evaluate the effective volume. However, this technique can be applied to any type of material. The effective volume calculated is shown with SEA in **Errore. L'origine riferimento non è stata trovata.**:

*Table 2 : Thermographic SEA*

| Thermographic method | | |
|---|---|---|
| **1,5 m/s (Specimen 1)** | | |
| **Effective Volume [cm$^3$]** | **Absorbed Energy [kJ]** | **Specific Energy Absorption [kJ/kg]** |
| 6.09 | 0.024 | 2.3 |
| **6 m/s (Specimen 4)** | | |
| **Effective Volume [cm$^3$]** | **Absorbed Energy [kJ]** | **Specific Energy Absorption [kJ/kg]** |
| 5.95 | 0.032 | 3.0 |

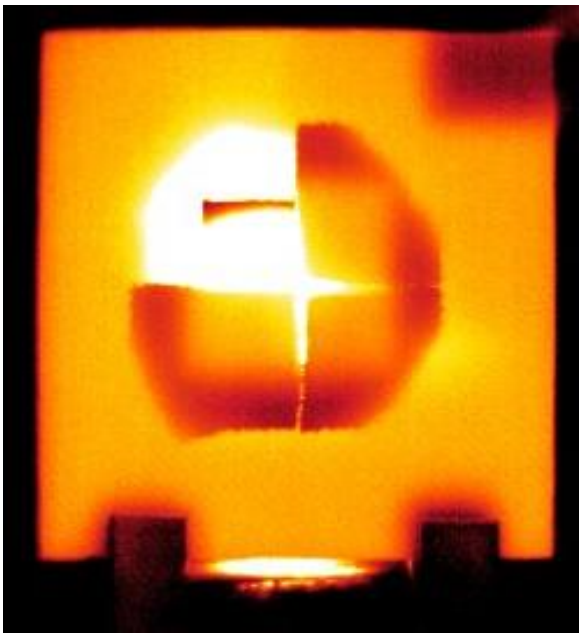

*Figure 8: SEA Thermographic analysis*

## Tomographic method

The final test method used to determine the effective volume is the X-ray Micro-tomography, since it allows to analyze the internal structure of the material and recreate the actual state of the specimen without destroying them. Computed tomography was born as medical inspection technique and natural evolution of x-ray radiography [14]. As for radiography, computed tomography is based on attenuation that an electromagnetic wave (a sufficiently high energy and frequency x-ray) undergoes when crossing a body. For tomography, multiple analysis are taken by changing the position of the x-ray source (or the specimen). By combining all the radiographic images through a program, a 3D model of the specimen is generated. The tomographic analysis were performed using an "phoenix v|tome|x" of General Electric® using a copper target and applying a voltage of 280 kV and a current of 180 µA in order to obtain a resolution in all three dimensions of 116 µm resolution. To analyze the images obtained, it was used the software VG-Studio Viewer®. The results obtained through tomographic method, as shown in With three-dimensional models of specimens obtained after impact, it is possible to analyze layer by layer the failure mechanisms of GFRP. The results have precision in the order of µm. Effective area that dissipated the impact energy is shown in Figure 10. It allows to analyzing the specimen throughout its thickness to recognize the phenomena that contributed to the fracture (delamination, fiber and matrix cracking). A precise volume and SEA can be evaluated for each individual specimen.

, are very similar to those obtained with the Thermographic method.

*Table 3: Tomographic SEA*

| **Tomographic method** | | |
|---|---|---|
| **1,5 m/s (Specimen 1)** | | |
| **Effective Volume [cm$^3$]** | **Absorbed Energy [kJ]** | **Specific Energy Absorption [kJ/kg]** |
| 6.11 | 0.024 | 2.3 |
| **6 m/s (Specimen 4)** | | |

| Effective Volume [$cm^3$] | Absorbed Energy [kJ] | Specific Energy Absorption [kJ/kg] |
|---|---|---|
| 6.05 | 0.032 | 2.9 |

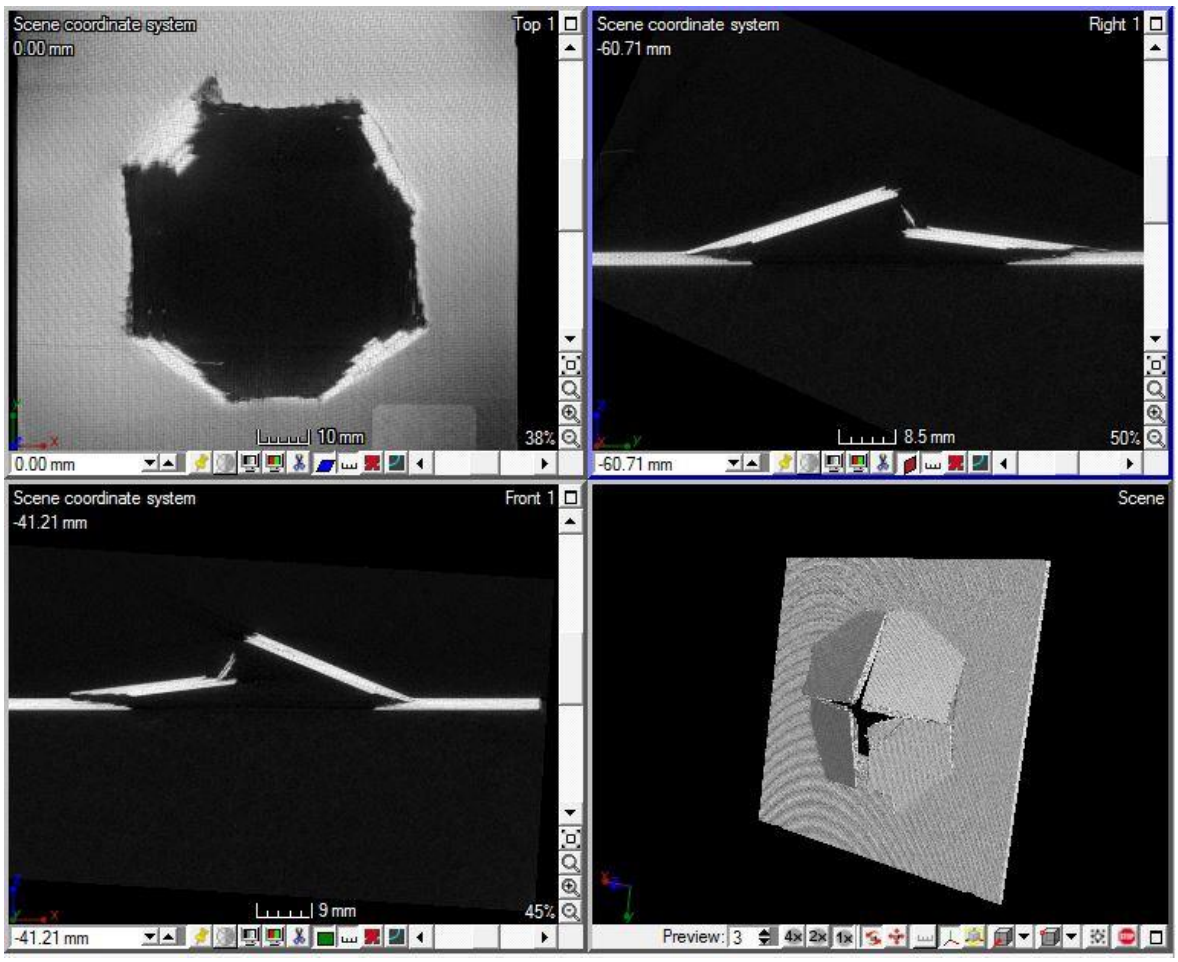


*Figure 9: Specimen analysis through VG-Studio Viewer*

With three-dimensional models of specimens obtained after impact, it is possible to analyze layer by layer the failure mechanisms of GFRP. The results have precision in the order of µm. Effective area that dissipated the impact energy is shown in Figure 10. It allows to analyzing the specimen throughout its thickness to recognize the phenomena that contributed to the fracture (delamination, fiber and matrix cracking). A precise volume and SEA can be evaluated for each individual specimen.

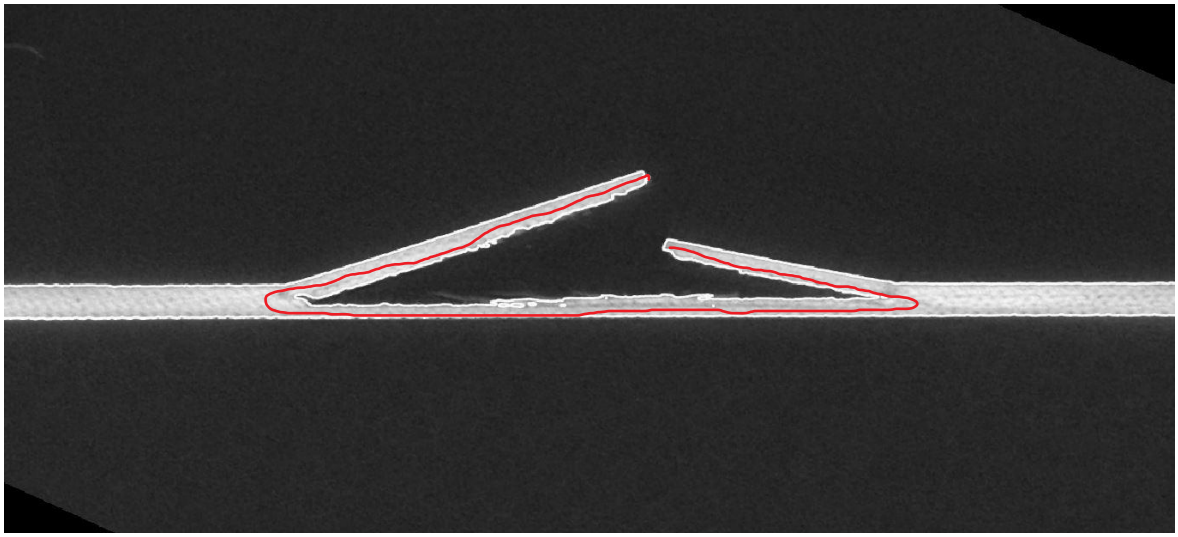

*Figure 10: Fracture analysis*

## Conclusion

The main aim of this study was to evaluate the absorption energy of specimens (epoxy resin reinforced with glass fibers E-Glass) during impact, which is represented as a specific coefficient called SEA. Table 5 shows the amount of energy absorbed per unit mass of the material during impact.

*Table 5: Final result comparison.*

| **1.5 m/s** | | | |
|---|---|---|---|
| | **Optical Method** | **Thermographic Method** | **Tomographic Method** |
| **Effective Volume [cm$^3$]** | 6.59 | 6.09 | 6.11 |
| **Specific Energy Absorption [kJ/kg]** | 2.1 | 2.3 | 2.3 |
| **6 m/s** | | | |
| | **Optical Method** | **Thermographic Method** | **Tomographic Method** |
| **Effective Volume [cm$^3$]** | 6.76 | 5.95 | 6.05 |
| **Specific Energy Absorption [kJ/kg]** | 2.6 | 3.0 | 2.9 |

A fast, easy and effective way to obtain this property has been defined as using tomographic method. This is obtained through compassion of three different commonly used analysis method (Optical, Thermographic and Tomographic) as shown in Figure 11:

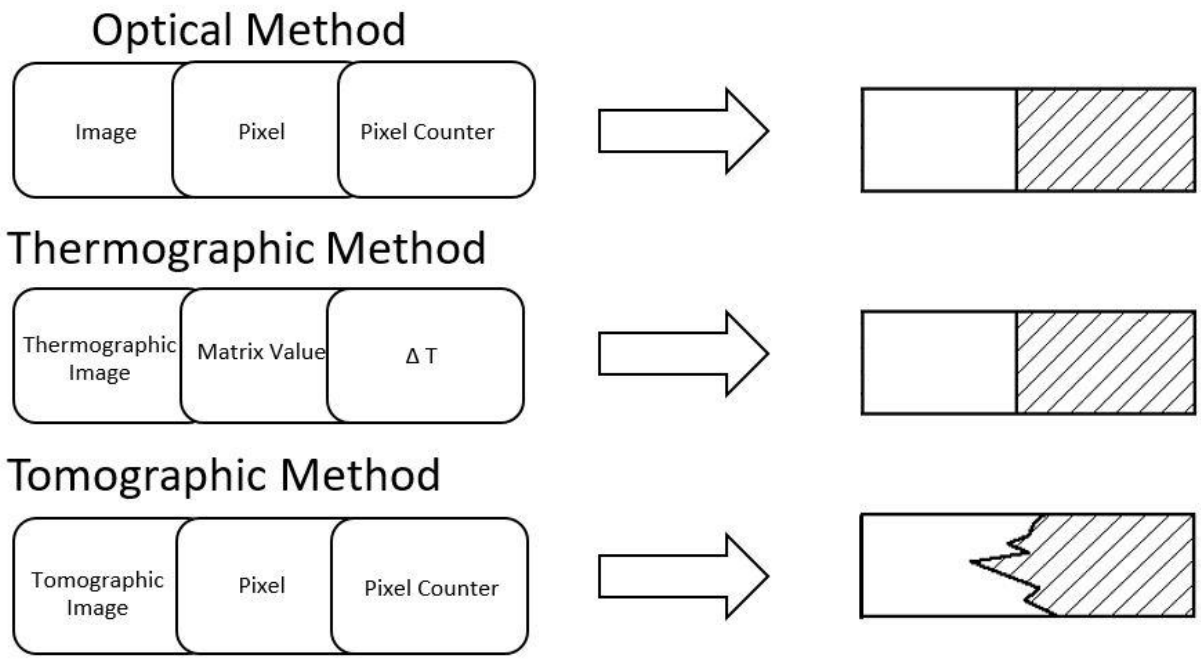


*Figure 11: Mesurement methods.*

- The optical method for the evaluation of the SEA greatly underestimate the effective volume of the material, such consequentially effects of the evaluation of SEA. This technique is proved to be inaccurate and unreliable. It is also limited that can be applied exclusively for transparent material (at least in the interested zone).
- Both the Thermographic method and Tomographic method does not have limitations for material transparency. The result obtained by both methods are very similar to each other. They are both suitable for the evaluation of SEA.
- Aa shown in Table 6, the Δ % referred to Tomographic method could be up to 20 % in Optical method, meanwhile it's below the 5 % in Thermographic case.

*Table 6: Error rate.*

| **1.5 m/s** | | | | | |
|---|---|---|---|---|---|
| | **Optical Method** | **Δ % to Tomographic** | **Thermographic Method** | **Δ % to Tomographic** | **Tomographic Method** |
| **Effective Volume [cm$^3$]** | 6.59 | + 7.85 % | 6.09 | + 0.3 % | 6.11 |
| **Specific Energy Absorption [kJ/kg]** | 2.1 | - 19.2 % | 2.3 | / | 2.3 |
| **6 m/s** | | | | | |
| **Effective Volume [cm$^3$]** | 6.76 | + 11.73 % | 5.95 | - 1.65 % | 6.05 |
| **Specific Energy Absorption [kJ/kg]** | 2.6 | - 10.3 % | 3.0 | + 3.4 % | 2.9 |

- Comparing thermographic and tomographic, the Thermographic is more cost effective, since the tomographic turns out to be more complicated and more expensive and cost more time to perform.

As it was done in this research, a full Tomographic analysis took an hour to finish, four times more than that required for a complete Thermographic analysis.

- Tomographic analysis is the most complete non-destructive evaluation technique for its high resolution and more straight-forward observation of the fracture phenomenon. Although it still presents several limitations, such as the size of the pieces to be analyzed need to be small, the analysis is more complicated and equipment is very expensive.
- Regarding the mechanical behavior of the material, it is important to note how the increase of the impact speed has changed the way material absorbs impact energy. This effect is probably due to the strain rate of the material, which will be analyzed in the future.
- These methods make it possible to obtain SEA of materials without resorting to expensive equipment for performing tubular specimen analysis. A correlation of analysis between planer specimen and tubular specimen will also be analyzed in the future.

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