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Impact Response of Carbon Fiber Composites: Comparison Between Epoxy and Bio-Based Epoxy Matrices

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Abstract. The elastic properties and the impact response of composite laminates made of carbon fibres (CFRP) and two different matrices, epoxy and bio-based epoxy, has been experimentally assessed with the Impulse Excitation Technique (IET) and with drop dart tests. Eight carbon twills (2 × 2) have been used to prepare the composite laminates with a traditional epoxy resin and an epoxy-based resin with 31% of bio content (glycerol in place of petroleum-based propylene).

The elastic properties of the two investigated composite plates have been found to be slightly different, if assessed with the IET. Similarly, the resin type has been found to not influence the impact response, for impact energy equal to 15 J (dart rebound) and to 30 J (dart penetration). For the range of investigated impact energies, it can be concluded that the bio-based resin can be used in place of a commonly used epoxy resin.

Keywords: Drop dart · sustainable resin · energy absorption · Impulse Excitation Technique

1 Introduction

The use of composite materials is extremely important to reach specific lightweight goals in different industrial fields (e.g., the aerospace or the automotive fields), such as reducing fuel consumption/emission or increasing the autonomy of electric vehicles.

However, the last challenge for the transportation industry is the design of new components by considering the Life Cycle Assessment and so reduce the overall carbon footprint [1]. Accordingly, new thermoplastic and bio-based resins have been developed and are currently commercially available and can substitute traditional resins that cannot be recycled. However, in order to ensure the structural integrity of components, the mechanical properties of composite made with bio-based resin should be experimentally assessed and compared to those of commonly used epoxy resin composite laminates. Among these, the assessment of the impact response is fundamental for composite materials. Indeed, technical literature has widely investigated the tolerance of composite materials to impact damage. Pursuing metal approaches, the residual load-bearing capability has been the first concern. However, the prediction of the post-impact

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load-bearing capability of a damaged composite structure is more difficult than in metals, as the damage zone is generally complex in nature. Great efforts have been thus made to improve the impact resistance of fibre composites, by focusing on the governing parameters related to the constituents. Another approach looks at the energy absorption aptitude of the composite structures.

Energy balances approaches particularly allow to evaluate the level of damage accumulation of composites during impact events. The manner in which composite materials respond to impact loading and dissipate the incident kinetic energy, E_i, is very different to that of metals. For low and intermediate impact energy, metals absorb energy through elastic and plastic deformation, whose consequences on the load-carrying capability are usually limited. At high energy, perforation may occur, and its effects can be predicted through fracture mechanics principles. In composites, whose plastic deformation is very limited if not null, the impacting energy E_i is dissipated both through elastic deformation and by fracturing. Net of the elastic energy E_{el}, whereby the impactor rebounds, the residual part of the incident energy is absorbed in creating large areas of fracture. Impact damages are thus strictly correlated to the absorbed energy E_{abs}, which can be in turn interpreted as a measure of the material damage [2].

This work aims at assessing the elastic properties and the impact response of two composite laminates made with carbon fibers and an epoxy resin and a bio-based epoxy resin commercially available. The two resins present a similar cost. The elastic properties have been assessed with the Impulse Excitation Technique [3]. Free fall drop dart impact tests at increasing impact energies have been carried out to assess the impact response. The peak force and absorbed energy have been compared in order to assess if the bio-based resin affects the impact response of the investigated composite laminates.

2 Materials and Methods

In the Section, the tested materials and the experimental setup are described. In Sect. 2.1, details on the preparation of the two tested composite laminate types are provided. In Sects. 2.2 and 2.3, the Impulse Excitation Technique (IET) employed for comparing the elastic properties and the testing configuration for assessing the impact response are described, respectively.

2.1 Materials

Composite laminates made of carbon fibres have been prepared with two different epoxy resins: a traditional commercially available epoxy resin IN2 (EasyComposite, UK) and an epoxy resin with 31% of bio content IB2 (EasyComposite, UK). The bio-content of the bio-based resin is due to the glycerol, plant derived, in place of petroleum-based propylene.

The two resins present similar mechanical properties that are reported in Table 1.

Table 1. Tensile and flexural properties of IN2 and IB2 resins

	IN2	IB2
Tensile strength [MPa]	68.5	65
Flexural strength [MPa]	118	107
Flexural modulus [GPa]	3.3	2.8
Elongation at break [%]	7.0	5.3

Composite laminates, 2mm thick (8 layers), were obtained by using vacuum infusion technique. The fabric is a 210 g and 2 × 2 carbon twill (Mitsubishi, JP). The fabric is characterized by a maximum tensile strength of 4120 MPa, a tensile modulus of 240 GPa and a maximum elongation of 1.8%. The two resins were degassed in a vacuum chamber before the infusion and cured for 24 h at room temperature and post-cured in the oven at 100 °C for 3 h.

2.2 Impulse Excitation Technique

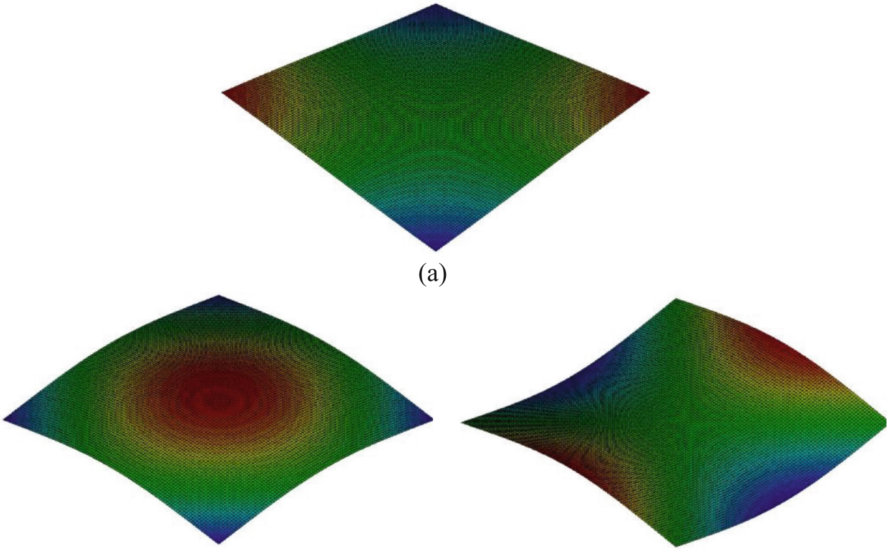
The elastic properties of the epoxy-based and bio-based resin composites are determined through the Impulse Excitation Technique (IET). The IET allows to characterize the elastic response specifically of the impacted plates and, in addition, its degradation after the impact.

In this work, the IET is used to compare the material properties of the two composites. It is assumed that the elastic properties of the two principal directions are equal, the plate is perfectly square, and the in-plane material principal directions are aligned to the edges of the plate. Under these assumptions, the equation $\frac{a}{b} = \left(\frac{E_{11}}{E_{22}}\right)^{\frac{1}{4}}$ is satisfied, being a and b the plate dimensions and E_{11} and E_{22} the in-plane Young's moduli. Therefore, the O and X modes can be properly excited and used to determine the elastic properties together with the torsional mode. Figure 1 depicts the modes here considered.

Following the methodology proposed by McIntyre and Woodhouse [4], the in-plane shear modulus G_{12} can be calculated from the torsional mode as:

$$G_{12} = 0.822\frac{f_T^2 \cdot \rho \cdot a^4}{h^2} \tag{1}$$

where f_T is the measured torsional frequency, ρ the material density and h the plate thickness.



(a)

(b)

(c)

Fig. 1. Mode shapes for the assessment of the elastic properties: a) torsional mode; b) O mode; c) X mode

The in-plane Young's moduli, E_{11} and E_{22}, and Poisson's ratio, ν_{12}, can be obtained from the O and X modes. The approximated formulas for the O and X frequencies were derived by McIntyre and Woodhouse [4] as:

$$\begin{aligned} f_O^2 &\cong \frac{h^2}{\rho \cdot a^4}\left(13 \cdot \sqrt{D_{11} \cdot D_{22}} + 4.4 \cdot D_{12}\right) \\ f_X^2 &\cong \frac{h^2}{\rho \cdot a^4}\left(13 \cdot \sqrt{D_{11} \cdot D_{22}} - 4.4 \cdot D_{12}\right) \end{aligned} \tag{2}$$

where

$$\begin{aligned} D_{11} &= \frac{E_{11}}{12 \cdot (1 - \nu_{12}\nu_{21})} \\ D_{22} &= \frac{E_{22}}{12 \cdot (1 - \nu_{12}\nu_{21})} \\ D_{12} &= 2 \cdot \nu_{12} \cdot D_{22} = 2 \cdot \nu_{21} \cdot D_{11} \end{aligned} \tag{3}$$

Considering that the elastic properties of the two principal directions are equal, we can compute D_{11}, D_{22} and D_{12} as:

$$\begin{aligned} D_{11} = D_{22} &= \left(f_0^2 + f_X^2\right)\frac{\rho \cdot a^4}{26 \cdot h^2} \\ D_{12} &= \left(f_0^2 + f_X^2\right)\frac{\rho \cdot a^4}{8.8 \cdot h^2} \end{aligned} \tag{4}$$

from which the Young's moduli and the Poisson's ratios can be calculated through Eqs. (3).

The experimental setup is shown in Fig. 2.

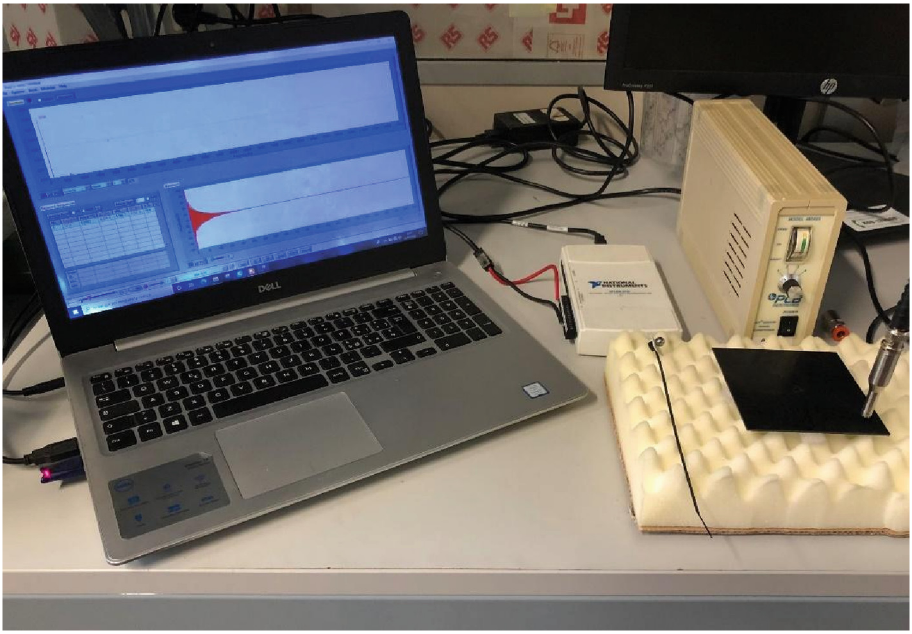


Fig. 2. Experimental setup for the IET tests

The plate was excited by impulse in accordance with the IET and the mechanical vibrations were measured through a microphone. The frequencies of interest were excited by properly providing the impulse and accordingly disposing the microphone for the acquisition. For example, for the O mode, the plate has been excited in the center and the vibrations have been acquired in correspondence of one of the corners.

The NI USB-6210 system was used for the analogic-to-digital conversion of the signal. In Buzz-o-sonic® environment, the fundamental resonant frequency was calculated through a FFT of the signal.

2.3 Impact Test Configuration

Impact tests have been carried out by using free fall drop dart testing machine (CEAST 9350 FRACTOVIS PLUS), which allows to assess the out of plane impact response of laminates in a speed range 0.77–24 m/s and with impact energy between 1J and 1800J. For a fixed impact speed, the impact energy is varied by changing the impact mass. A hemispherical impact tup with 20 mm diameter has been used. 100 × 100 mm squared plates have been used for the impact tests, with a 76 mm diameter circular unclamped region, in agreement with the recommendations of the ASTM standard [5]. The force signal during the impact tests has been acquired with a piezoelectric load cell (203B by PCB Piezotronics), located behind the impactor tup, at a sample rate of 1 MHz. The signal is thereafter amplified and acquired by using a National Instrument acquisition system. Furthermore, the impact speed just before the impact is measured with an optoelectronic device, which is also used as a trigger to start the acquisition of the force signal. For each test, therefore, the impact velocity and the force-time signal are acquired. The force-time signal has been moreover smoothed with a moving average filter to minimize the acquisition noise.

Figure 3 shows a schematic image of the impact test configuration and of the clamping system, which ensures a uniform pressure distribution on the clamped region.

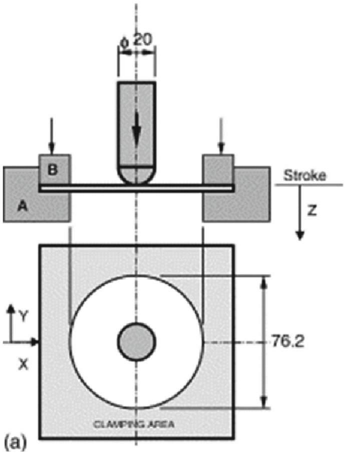


Fig. 3. Schematic image of the clamping system [6].

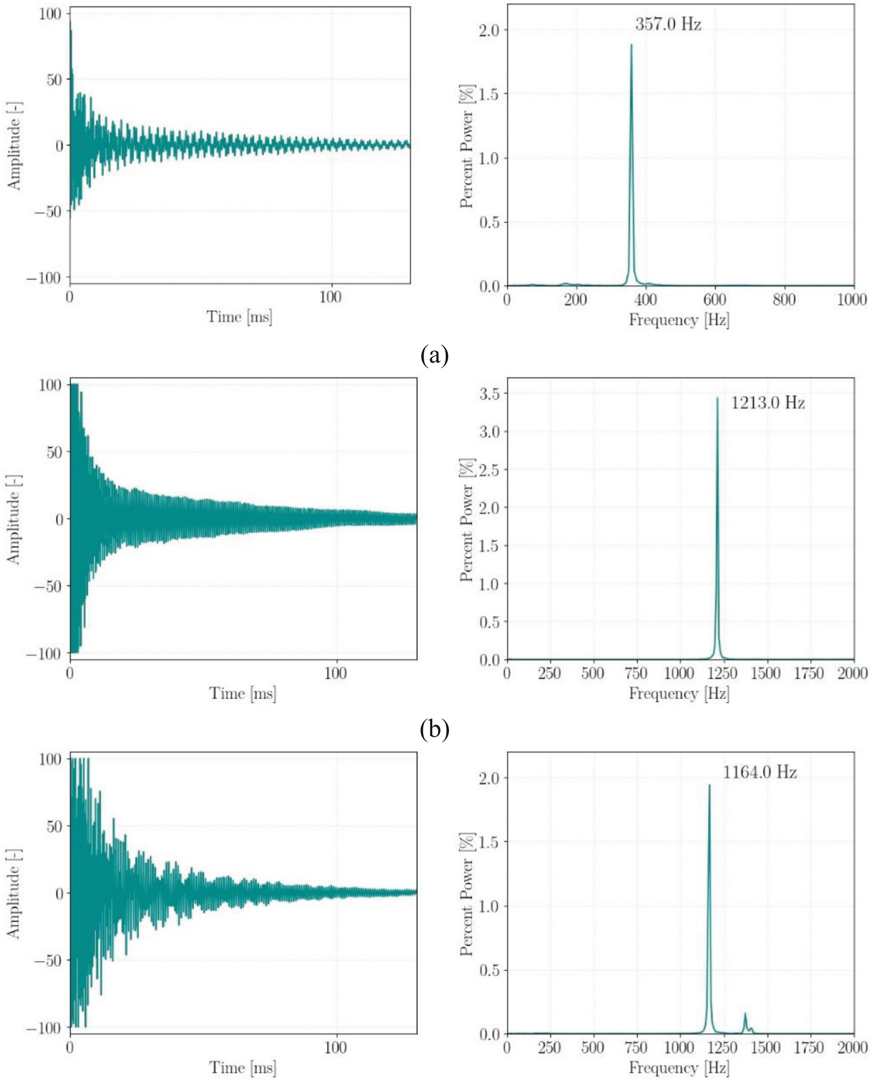
Impact tests were carried out with a mass of 15.9 kg and two impact speeds, namely at 1.4 m/s and 2 m/s, corresponding to impact energies of 15 J and 30 J. These two impact energies have been selected to analyze the response of the tested laminates without perforation (impact energy of 15 J) and when perforation occurs (impact energy of 30 J). Three repetitions for each configuration have been carried out. However, for an impact energy of 15 J and the composite with epoxy resin, only two valid tests are available.

3 Experimental Results

In this Section the experimental results are analyzed. In particular, the elastic properties assessed with the IET are compared in Sect. 3.1, whereas the results of the impact tests are analyzed in Sect. 3.2.

3.1 Elastic Properties Assessment

The elastic properties of the composite plates have been determined through the IET and the methodology described in Sect. 2.2. The use of the IET allows to assess the elastic properties of each impacted plate, which can be then correlated to the impact response. In addition, the material degradation after the impact can be quantitatively assessed. In this regard, it is worth noticing that the damage would be consistently involved in the O mode vibration, as the plate is impacted in the center, thus affecting in turn its resonant frequency [7].



(a)

(b)

(c)

Fig. 4. Signals in time and frequency response functions of the retained modes for the epoxy-based composite: a) torsional mode; b) O mode; c) X mode

Figure 4 shows typical signals in time and the corresponding frequency response functions (FRFs) of the three retained modes.

These FRFs particularly refer to an epoxy-based plate. In all cases, the resonant pick is clearly recognizable and well distinguished from the other resonances of the plate.

In Table 2, the determined elastic properties are reported for the epoxy and bio-based epoxy composites.

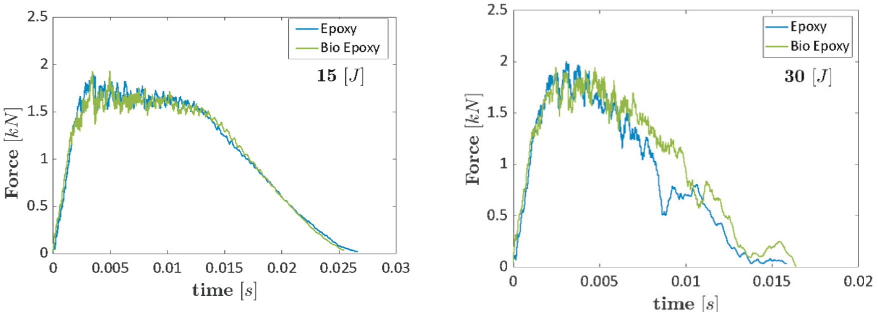
Table 2. Material properties of the tested materials obtained through IET tests

Material	E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	ν_{12} [−]
Epoxy resin composite	46.0 ± 1.6	46.0 ± 1.6	3.6 ± 0.3	0.054 ± 0.02
Bio-based epoxy resin composite	44.9 ± 1.8	44.9 ± 1.8	3.15 ± 0.2	0.047 ± 0.01

The elastic properties of the two materials are very similar, being those of the bio-based epoxy laminate slightly lower than the corresponding ones of the epoxy composite. Also, the confidence intervals are similar, being the same the manufacturing process. For a better comparison, a thermogravimetric analysis (TGA) could reveal the fiber volume fraction of the composites.

3.2 Impact Test Response Analysis

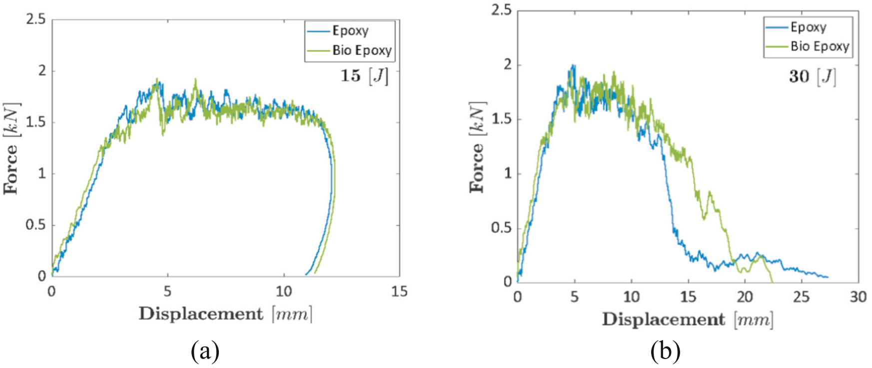
In this Section, the impact properties are analyzed and compared. Figure 5 shows one representative acquired force-time curve for the epoxy and the bio-based composite laminates at an impact energy of 15 J (Fig. 5a) and 30 J (Fig. 5b).



(a) (b)

Fig. 5. Representative force-time curves for the epoxy and the bio-based composite laminates: a) impact energy of 15 J; b) impact energy of 30 J.

Figure 5 illustrates that the composite obtained with the epoxy and the bio-based resins shows the same impact response with respect to time. However, for a proper analysis of the absorbing capabilities, the force-displacement curves and the absorbed energy should be compared. The displacement has been obtained through a double integration of the acceleration signal, obtained from the acquired force signal, with respect to time [8]. Figure 6 compares the force-displacement curve for impact energy of 15 J (Fig. 6a) and 30 J (Fig. 6b).



(a) (b)

Fig. 6. Force with respect to displacement curves for the epoxy and the bio-based composite laminates; a) impact energy of 15 J; impact energy of 30 J.

Figure 6 shows that the resin type does not influence the impact response of the tested composite laminates. For an impact energy of 15 J, the laminates are not perforated, with the curves showing a rebound of the dart of about 1 mm. An impact energy of 15 J is not enough to induce a complete failure with perforation. The slope in the first region and the peak forces are the same. On the other hand, with an impact energy of 30 J, the perforation is achieved, with the displacement continuously increasing during the test. Even for this impact energy inducing a perforation of the composite laminates, the resin type does not influence the impact properties. Figure 7 shows an image of the tested composite laminates after the impact tests: Fig. 7 for an impact energy of 15 J, whereas Fig. 7 b for an impact energy of 30 J. Similar fracture surface morphologies have been found for the epoxy and the bio-based composite plates.

Figure 7a confirms that an impact energy of 15 J does not induce a complete perforation of the laminate, with cracks starting to propagate from the impact area along the horizontal and vertical directions. On the other hand, at 30 J, the signs of the perforation are clear (Fig. 7b), with cracks propagating from the region where the impact has occurred.


(a) (b)

Fig. 7. Composite plates after the impact tests: a) impact energy of 15 J; b) impact energy of 30 J.

Table 3 finally compares the impact response of the two tested composite laminates. In particular, the peak force and the impact energy are considered. The average value (between the three tests) and the standard deviation (within round brackets) are reported.

Table 3. Comparison of the energy absorbing properties of the two investigated laminates

	Epoxy resin		Bio-based epoxy	
	15 J	30 J	15 J	30 J
Peak force [N]	1891	1988 (±27)	1882 (±42)	1902 (±75)
Absorbed energy [J]	16.8	21.3(±1.3)	16.7(±0.1)	23.1(±2.7)

According to Table 3, the peak force increases with the impact energy and the increment is larger for the epoxy resin. The peak force is, moreover, slightly larger for the epoxy resin composite at the two investigated impact responses, but the difference is limited. On the other hand, the absorbed energy is the same for impact energy of 15 J, whereas it is larger for the bio-based resin at the impact energy of 30 J. However, due to the larger experimental scatter at this energy level, the difference between the absorbed energy of the epoxy resin composite and the bio-based resin composite cannot be considered significant.

To conclude, for the range of investigated impact energy, the impact response of the epoxy and the bio-based resin is the same.

4 Conclusions

In the present work, the elastic properties and the impact response of two composite laminates made by 8 layers of woven carbon fibres with epoxy and bio-based epoxy resins commercially available were investigated.

The elastic properties were assessed through the Impulse Excitation Technique (IET) directly on the square plate subjected to impact test. The torsional mode, O mode and X mode have been used to determine the elastic properties through a methodology derived from McIntyre and Woodhouse [4]. Results showed that the elastic properties of the two materials are very similar, being those of the bio-based epoxy laminate slightly lower than the corresponding ones of the epoxy composite. Even though the manufacturing process was the same, a thermogravimetric analysis (TGA) will be considered in the future for a better comparison of the material properties.

The impact response was experimentally assessed with free-falling dart impact tests at two impact energies, 15 J (rebound of the dart) and 30 J (perforation of the laminates). For the range of investigated impact energies, it was experimentally found that the CFRP laminates prepared with the two resins are characterized by a similar impact response, with the peak forces and the absorbed energies showing almost the same values.

According to the analyses carried out in the paper, it can be concluded that the investigated commercially available bio-based resins can be used in place of the epoxy resin since it does not affect its elastic properties, measured with the IET, and the impact response.

References

1. Ciardiello, R.: The mechanical performance of re-bonded and healed adhesive joints activable through induction heating systems. Materials **14**(21), 6351 (2021)
2. Belingardi, G., Cavatorta, M.P., Paolino, D.S.: A new damage index to monitor the range of the penetration process in thick laminates. Compos. Sci. Technol. **68**(13), 2646–2652 (2008)
3. ASTM E1876-21. Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's ratio by Impulse Excitation of Vibration (2015)
4. McIntyre, M.E., Woodhouse, J.: On measuring the elastic and damping constants of orthotropic sheet materials. Acta Metall. **36**, 1397–1416 (1988)
5. ASTM D5628-10. Standard Test Method for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Falling Dart (Tup or Falling Mass). ASTM International: West Conshohocken (2010)
6. Elmarakbi, A., et al.: Effect of graphene nanoplatelets on the impact response of a carbon fibre reinforced composite. Mater. Today Commun. **25**, 101530 (2020)
7. Boursier Niutta, C.: Residual elastic response in damaged woven laminates through local Impulse Excitation Technique. Compos. Struct. **293**, 115723 (2020)
8. Belingardi, G., Vadori, R.: Low velocity impact tests of laminate glass-fiber-epoxy matrix composite material plates. Int. J. Impact Eng **27**(2), 213–229 (2002)