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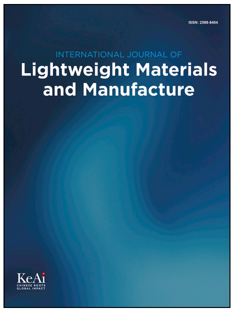

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Ultrasonic inspection of composites materials: application to detect impact damage

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Abstract

Failures detection in composite laminates is complicated respect to conventional non-destructive testings for metal structures, due to their sensibility to echoes drown in noise depending by the different properties of the constituent materials and the multi-layered composites structures. The latter, in particular, are sensitive to impact damage and also a low-energy impact can results in a severe loss of the load capacity as a result of delamination. In this study, the effectiveness of the detection of the damage in low-velocity impacts in several different composite laminates, at different energy levels, is investigated by using Ultrasonic Technique. The latter technique was adopted to verify its capability to afford info on the shape and the size of the delamination, also in the presence of entirely different parameters. It was useful even to test the influence of different factors on the dynamic behavior of the studied composites. Pulse-echo method with faced array transducers (f=5MHz) was used to diffuse and receive ultrasound waves. The results provided information useful to understand the damage mechanisms and the onset and the propagation of the damage.

Keywords: ultrasonic; impact behaviour; composite materials

1. Introduction

Composite materials have gained significant interest in the automotive, naval and aerospace industries due to their excellent strength respect to the weight, after damage resistance and the possibility of structures of complex shapes [1-3]. Several procedures exist now for moulding composites objects ranging from simple manual technologies to more classy ones, autoclave for example. Each method has its particular benefits and limits to reach the essential technical performance at a low cost. The manufacturing technologies for composite materials have the potential to introduce several defects.

However, to guarantee structural integrity and safety of composite structures, the latter should be inspected periodically during their life. Inspection of composite materials poses a particular challenge since the materials are non-homogeneous and anisotropic with a consecutive complex mechanism of damage formation [4-6].

In service, composites are subjected to static, fatigue and impact loads that can degrade the performances of the materials. Composites can also be exposed to extreme temperatures and can be in contact with water, extreme conditions that significantly influence the performances. The several different loads can cause matrix cracking, fibre debonding, delamination and fibre breakage. An impact even if with low-energy leads to a severe failing of the load ability due to the caused delamination. A low-velocity impact loading causes non visible damages between the layers, difficult to be detected without dedicated methods. Typical composite damage is also labelled as barely visible impact damage (BVID) because composites do not show any visible external damage even if there is delamination between internal layers [7-11]. The different kind of damages has some effect on the performance of the composites, reducing their modulus and compression strength.

Several non-destructive testing techniques (NTD) have been developed for composites analysis purpose, but none of them can be considered exhaustive. Each method presents limitations and, often, it is necessary to deduction between sound and damaged materials at the edge of the related noises of the instrument. It is good to choose the suitable method for the detailed application but, often, it is better to use more than one method for a combined approach. It is worth noting that the ultrasonic technique (US) is one of the most useful universal NTD permitting to detect the different damages. There are several papers on this method applied to composite structures [12-15]. In this paper, the experimental results obtained by an ultrasonic methodology on impacted laminates, are described. The ultrasonic system is in the form of reflection and has been applied on several composite materials for the detection of the damages inside the laminate extension.

First of all, the main objective concerns the better evaluation of the system abilities in detecting the damage. Then, the influence of acoustic attenuation was inspected.

Different composite laminates were tested at the aim of the analysis. Materials typical for aerospace applications like glass(GFRP) and carbon fibre (CFRP) reinforced polymers with low signal attenuation, and laminates with higher attenuation as polymers reinforced by basalt fibres (BFRP), were analysed.

In all the cases, the inside damage was obtained by a low velocity impact test, achieved using a drop weight machine with a cilyndrical impactor with a sensorized hemispherical head 19.8 mm in diameter. The impact tests were performed at different impact energies to detect damages and study the start and propagation of the same.

1. Materials and methods

2.1 Materials

The study was addressed to examine the performance of different composite laminates inspected by ultrasonic techniques. Due to the anisotropy characteristic of the composite materials, it is complicated to set the ultrasound velocity, as above indicated, depending on the specific resin, fibre, stacking sequences and fibre orientation. The diverse types of material or fibre content (V_f) can influence the ability of ultrasounds to detect the defect due to a higher amount of ultrasound waves reflections in different ways. The first structure was produced as GFRP laminates overlapping unidirectional layers of E-glass fibre following the $[(0), (90)]_n$, stacking sequence, n = 8. Two different resins, epoxy

SX10 and vinylester Reichhold Hydrex, were used to infuse the fibre. The final laminates have nominal thicknesses in the range 3.8±0.2 mm. The final V_f = 48% was obtained.

The second investigated structure was manufactured by overlapping T700 fabrics made by carbon fibres 300 g/sqm, 3.9±0.1 mm thickness The samples were fabricated by vacuum infusion by using vinyl ester resin above reported. V_f was 51%.

Last examined structure was produced by overlapping plain-woven basalt fibre (Basaltex NV). The composites were realised by resin vacuum infusion technology, and a vynilester infusion system by Crystic Resin VE679PA was used to infuse the fibres. The fabric layers were stacked to obtain a nominal thickness 4±0.1 mm and a V_f equal 55%.

The damage was obtained by impact tests carried out at increasing impact energy levels equal to 25, 50, 75% [16]. The coupons, 100×150 mm^2, cut from the original panels, were clamped as suggested by the ASTM D7137 Standard and tested by the impact test machine, Ceast/Instron. A mass of 3.640 kg, combined with the drop heights to obtain the used impact energies, was considered.

2.2 Non-destructive inspection technique

5 MHz head (M2M Multi Pocket system, Phased Array Probe, 5 MHz Linear Array, 64 Elements) was used for the ultrasonic scans. See figure 1.

[insert Figure 1.]

The system is a multi-channel ultrasonic system based on the principle of the time-delayed triggering of the diffusing transducers, combined with a time corrected receiving of the signals. The advantage of the phased array is that it is possible to produce the ultrasonic beam with the incidence angle and focal distance controlled electronically. It is possible to provide the beam focused or directed through the laminate to be examined and the opportunity of analyse complex shapes. The other significant points are the capability to visualize the beam steering using angular beam scan image, and the advantage that the beam can be focused everywhere. Furthermore, the used phased array provides high efficiency of the data in mixture with extraordinary resolutions respect to traditional methods. Only few studies are concentrated on the use of phased array ultrasonic methods to composite laminates [18-21]. The rising adoption of phased array ultrasonic tests, valid to the materials under study in manufacturing processes and care phases, emphasize the necessity for additional investigations to enrich the understanding of damage detection in composite laminates.

The probe with a low frequency of f = 5 MHz has been adopted for the significant lowering of the attenuation of the recorded signal and useful measurements [13, 14].

The probe is used to emit and receive the ultrasound waves. The pulse-echo technique [12] allows the reception of information about internal damages. Short-duration pulses are spread into the region impacted and the echo signals caused by wave scattering and reflection are recorded and showed (A-scan). The depth of material is obtained from the delay between pulse diffusion and echo treatment. On the undamaged sample it is poossible to obtain the correct plate thickness and the calibration of the acquisition system (Fig. 2). The speed of the sound propagation through the material is equal to 2500 mm/s [14].

[insert Figure 2.]

C-scan inspections allows to send a plane view of specimens, caught by using high valuation before and after impacts. C-scan represents the reconstruction of the internal damage along the thickness, reported in one plane. Using the image obtained by adeguately setting the Gate, a lighter image of the internal delamination iss obtained, and the dimensions of the area scanned and of the specimen, the magnitude of the defect can be quantified. Thanks to the mode of detection as Echo Max the gate has been set and only the peak that exceeds is recorded. The C-scan is visualized by different colours, black only if the signal could not exceed the threshold. The delaminated area is imported in a CAD software (Image J) where it is bordered and measured.

After the impact tests, the plastic deformation impressed by the impactor on the material was observed by visual inspection by confocal microscope, Leica DCM3D.

3. Results and discussion

In figure 3, the A-scan of GFRP in the vinyl ester (a) and epoxy resin (b) is reported. The A-scan results in the Amplitude of the ultrasound signal versus the thickness of the analysed specimen and it is useful to calibrate the system for the acquisition of the analysis. Due to the anisotropy characteristic of the composite materials, it is complicated to set the ultrasound velocity, as above indicated, depending on the specific resin, fibre, stacking sequences and fibre orientation. The acquisition system gives the possibility to use a gain to amplify the default signal transmitted when the attenuation of the signal is very high, or it is challenging to detect the last echo. However, even if a different gain for the Amplitude of the signal (5 dB for the vinilester sample and 0 dB for epoxy one), it is possible to note that the A-scan on vynilester resin still results to be the worst (Figure 3a). In fact, from the duration of the signal, it is possible to evaluate the resolving power of the instrument-transducer unit that is the ability to detect two or more close discontinuities. The duration of the emission pulse coincides with the time in which the amplifier is saturated by the impulse of the excitation, and it is not able to receive echo signals. In other words, during the pulse emission, it is not possible to receive signals of ultrasound echoes.

[insert Figure 3.]

This duration reflects the near resolver power (dead zone) because the amplifier needs a specific time to go from transmission to signal reception. The dead zone (Fig. 3) is the length in millimetres of the material affected by the emission pulse in which it is not possible to detect echoes from reflections due to discontinuities. Thus, the larger the dead zone is, the more challenging it is to locate the first echo of the signal accurately.

On the contrary, the far resolver power, or, power resolver, is the ability of the instrument-cable-transducer system to distinguish in separate signals the echoes from two reflectors having ultrasound paths not very different from each other. The C-scan acquisitions on specimens only impacted at energy $U=50\%U_p$ are reported in figures 4b, 5b, 6b and 7b for all the composites tested. The C-scan is a reconstruction of the ply by ply damage. The result is reported on a single plane where it is possible to identify the damage shape and extension. It is possible to note that there have been significant problems on vinylester laminates (Figure 4) in particular, due to the specific resin. The C-scan acquisition of the epoxy sample (Figure 5b) is more precise and more defined than the vinylester one (Figure 4b). Moreover, the flat smooth surface due to the presence of fibres, results in higher resistance to the slide of the probe, causing many disturbing reflections. The different colours of the acquired images depend on the roughness of the surface, and the gain used to improve the C-scan image without altering the real acquisition.

[insert Figure 4.]

[insert Figure 5.]

Another disturbing element occurs when the scanned surface is the one on the back of the panel, opposite to the impacted surface because a small rise of signal amplitude is generated and it interferes with the surface probe coupling. As a result, the select of the right Gate for a good image was more complicated. Figures 4 and 5 show the pictures of the impacted side (a) and the C-scan acquisition (b) for vinyl ester (Figure 4) and epoxy (Figure 5) resin, respectively. Also, from the pictures, it is possible to note a less extension of the damage on epoxy laminates (Figure 4a) that seems to be more confined under the impact point.

The same analysis was done on CFRP and BFRP laminates in the vynilester resin (Figures 6 and Figure 7).

[insert Figure 6.]

[insert Figure 7.]

C-scan on BFRP sample (Figure 7b) was revealed brighter and more defined image respect to the CFRP (Figure 6b). In particular, in Figures 6 and 7 the front side picture and the C-scan on both materials impacted with the same impact energy of the previous case, U = 50%U_p, are reported. In the case fo basalt laminate (Figure 7), it is possible to see there is no propagation of the delamination that is confined in the area corresponding to the penetrator/surface contact point. In this case, the C-scan acquisition (Figure 7b) was revealed brighter and more defined image respect to CFRP (Figure 6b).

Also, the non-destructive inspection was revealed to be very useful for the CFRP material here investigated. The damage on the front side of the impacted CFRP laminates is not visible (Figure 6a), unlike what happens on the back side (Figure 8), revealed by ultrasound images (Figure 6b). Probably, due to the large bundle of fibres, there was a recovery of the local deformation [17].

[insert Figure 8.]

The analysis of the load curve gives useful information. In figure 9, three different load-displacement curves at penetration for CFRP, GFRP and BFRP, are compared. It is possible to observe that all the composite materials tested are penetrated. In particular, the CFRP one shows a higher maximum load and a higher rigidity than the other materials. On the other hand, the BFRP sample shows penetration energy, Up, higher than the CFRP material and a maximum load, Fmax, similar to the GFRP one, resulting in a good compromise between the traditional composites.

[insert Figure 9.]

[insert Figure 10.]

To validate what asserted, Figure 10 shows the comparison between the delaminated areas, A, for all the tested specimens. As expected, the delaminated area, A, increases as the impact energy, U, increases and it is lower on the BFRP system. In this last case, the delamination area, A, is concentrated in the area under the contact between the impactor and the surface, as indicated above (Figure 7).

4. Conclusions

The detection of the damage in different composite systems (CFRP, GFRP and BFRP in epoxy and vynilester resin), in different test conditions and at different energy levels, is investigated by Ultrasonic technique to give information on the the extent and the form of the delamination in order to compare the dynamic behavior of different composite materials by a NDT . Pulse-echo method with faced array transducers (f=5MHz) was used to transmit and receive ultrasound signals. The results supplied useful information about the mechanisms of damage and the onset and propagation of the damage. In particular, the A-scan acquisition (Amplitude versus thickness) shows a higher signal absorption in the vynilester composites and the consequent higher difficulty to detect the top and the bottom signal.

In terms of delamination, carrying out the ply by ply (C-scan), reconstruction of low-velocity impact damage, there have been significant problems, especially with the vinylester panels due to the particular kind of resin and a flat smooth surface. When the epoxy resin was used, the damage image was revealed brighter and more defined with the following advantage to get more information on about the dynamic behaviour. Fixed the resin, the same analysis was done on CFRP and BFRP laminates. The latter, show a lower propagation of the delamination than the others: the damage seems to be confined under the contact area between the penetrator and the surface. So, the BFRP composite showing also penetration energy, U_p, higher than the CFRP and GFRP ones, results in a good compromise between the traditional composites tested.

Conflicts of interest

The authors have no memberships with or involvement in any association or entity with any financial, or non-financial interest in the topic matter or materials discussed in this manuscript.

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Figure Captions

Figure 1. *Ultrasound System and phased array used.*

Figure 2. *A-scan of undamaged sample: calibration.*

Figure 3. *GFRP A-scan U=10J (a) vynilester; (b) epoxy.*

Figure 4. *GFRP vinylester U=10J (a) picture; (b) C-scan.*

Figure 5. *GFRP epoxy U=10J (a) picture (b) C-scan.*

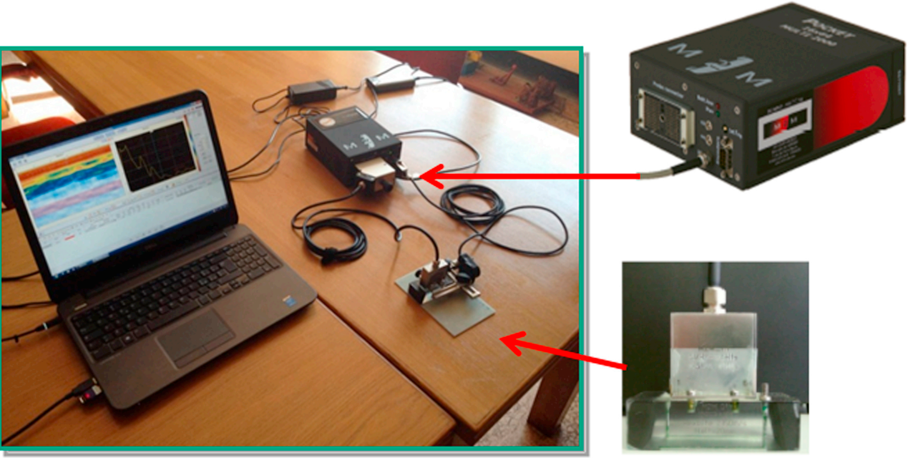
Figure 6. *CFRP epoxy U=10J (a) picture (b) C-scan.*

Figure 7. *BFRP epoxy U=50%Up (a) picture (b) C-scan.*

Figure 8. *CFRP vinylester U=50%Up, impact backside.*

Figure 9. *Load-displacement curves at penetration for all tested systems*

Figure 10. *Delamination area, A, versus the impact energy, U.*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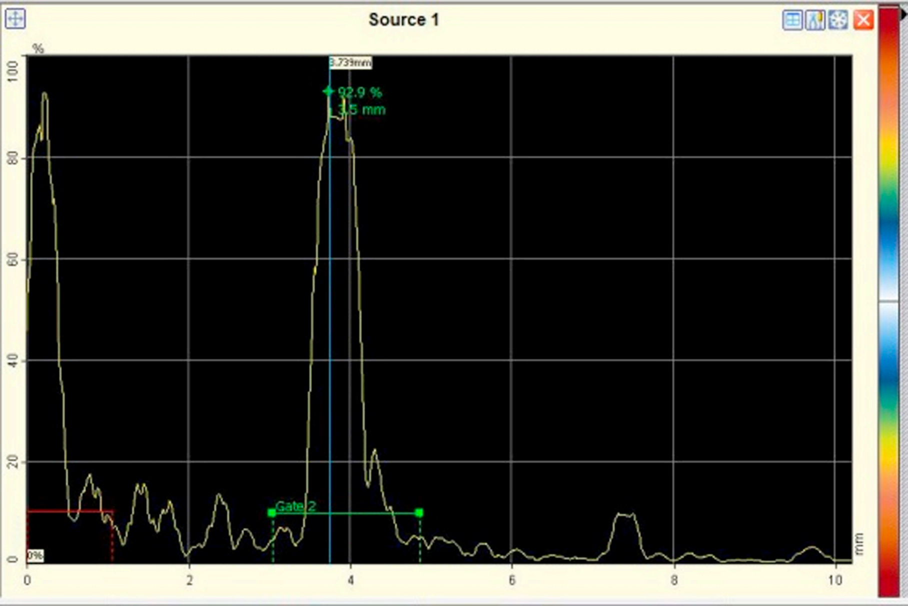
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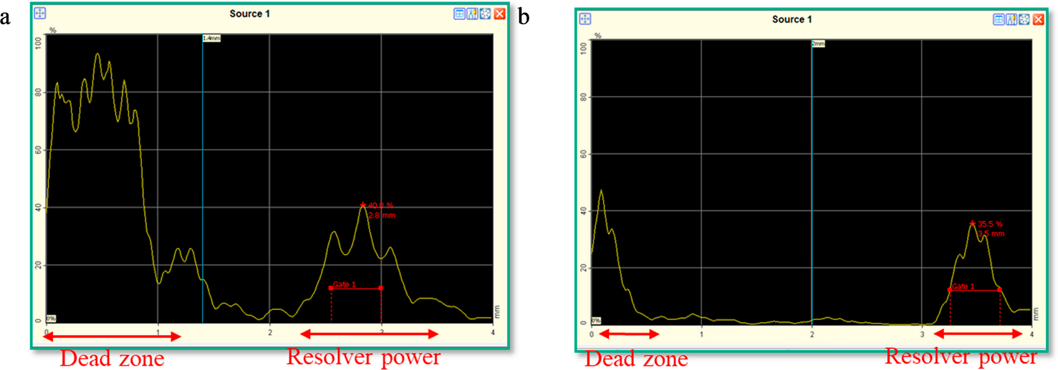
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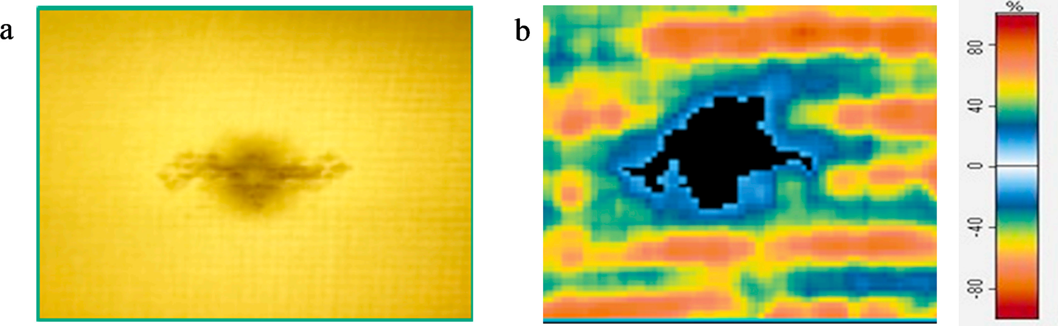
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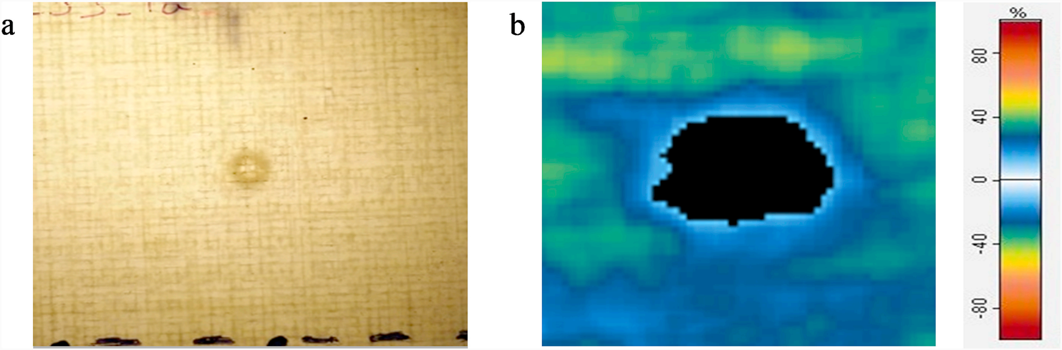
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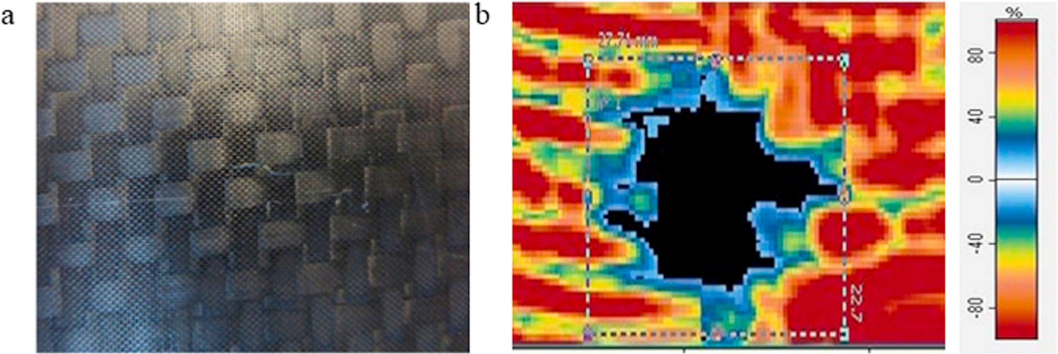
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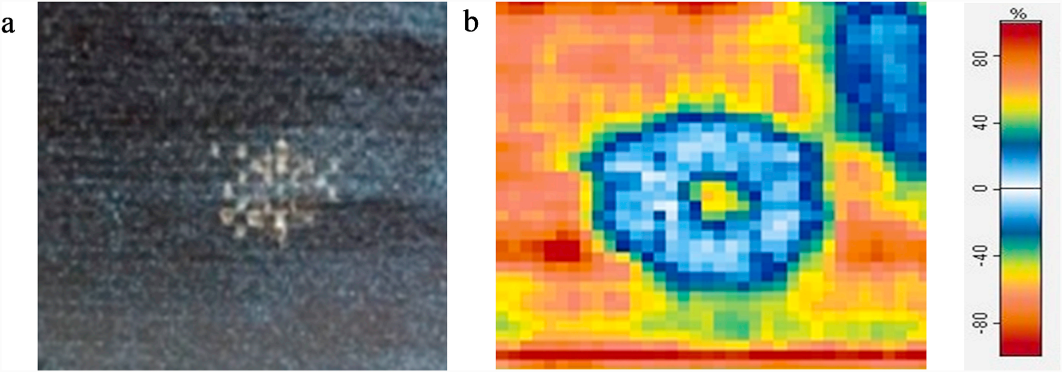
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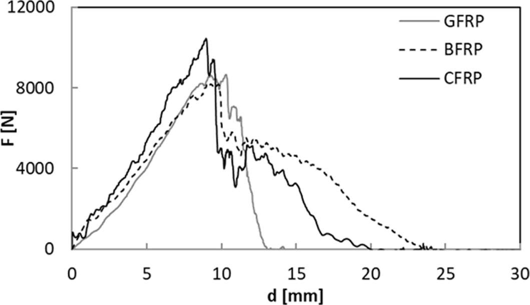
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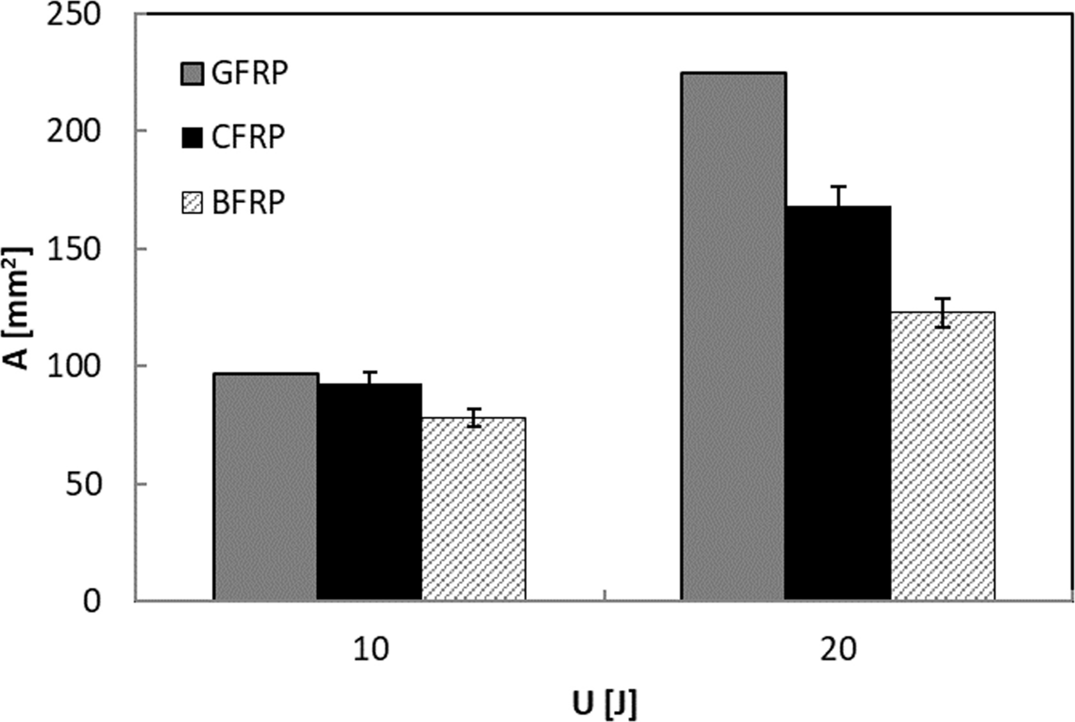
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Valentina Lopresto declares that there isn't any conflit of interest about the submitted paper:

Ultrasonic inspection of composites materials: application to detect impact damage

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