A THERMOPLASTIC POLYMER COATING FOR IMPROVED IMPACT RESISTANCE OF RAILWAYS CFRP LAMINATES

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Abstract

Due to the superior specific mechanical properties and low density of composite materials, their demand has risen prolifically within several industrial fields over the last decade including railway industry. The latter considers composite materials as a much more attractive alternative to standard metallic solutions. However, while composite materials have already been used in the manufacturing of parts of rolling stock (overhead structures, cab fronts, seats, doors), there is currently no procedure to certify a rail vehicle built entirely - or in large part - from non-metallic materials.

In this context, safety based technological improvements criteria are mandatory for any transportation system. One of the safety features for a train is the missile protection, which indicates that the vehicle shell must not permit any flying objects to penetrate the coach/vehicle. Hence, the analysis of the characteristics of composite impact damage is mandatory to apply mitigation actions against structural integrity detriment, also considering that even though regulation requirements for composite structures exist, they are not comprehensive enough to improve the overall structural safety.

The aim of this paper was design and characterisation of Carbon Fibres Reinforced Polymer (CFRP) laminates hybridised with thermoplastic polyurethane (TPU), to enhance impact energy absorption and satisfy light weight requirements.

In order to simulate flying ballast, a Low Velocity Impact (LVI) tests campaign was carried out at different impact energy levels (2 J and 3 J) by mean of a drop tower impact test on 150 x 100 mm CFRP specimens with and without TPU. Impacted samples were subjected to a non-destructive analysis campaign using Phased array to evaluate the extent of internal damaged areas and the results showed a significant benefit towards impact damage tolerance when a thin polyurethane layer is applied on CFRP components. Results from the experimental campaign show significant benefit against impact damage tolerance due to the thermoplastic material damping properties which are able to modify the energy absorption mechanism, reducing the extent of the internal delamination.

1. Introduction

It is well known that composite materials have a wide range of applications in several industrial sectors, such as aerospace, automotive, marine, and military [1–5], while they are still a relative novelty for the railway industry. However, in recent times the interest in these materials is risen also in this sector, due to the remarkable savings in terms of track wear, energy and maintenance costs maintenance costs connected with the replacement of traditional metal parts with composites. For example, Kawasaki realised an innovative CFRP elastic element of the primary suspension, named "efWING" [6], Beakbane Ltd proposed a composite stone guard to protect high-speed train under side [7], while Magma Structures realised a vehicle bogie frame made of recycled CFRP [8] . In [9], a sandwich structure made of glass fibre epoxy sheets with a polymeric foam core was experimentally investigated for the manufacturing of the front structure of a high speed train, and it was found that significant improvements can be achieved by adding resin walls within the foam. Composite materials were also numerically and experimentally investigated for the realisation of car-body made of hybrid CF1263 carbon/epoxy and Al honeycombs [10], GFRP bogie frames [11], shock absorbers [12], and other railway components [13]. In [14], a sandwich composite structure for the body shell of a of car-body was investigated, and a maximum stress value of about 12% the strength of the utilised composite material was found.

Despite high specific in-plane mechanical performances compared to conventional materials, one of the most critical problems of composite materials is their response to external impacts. Indeed, due to their low resistance against out-of-plane loads, after a collision event composite structures can experience damage that can be undetectable by visual inspection (Barely Visible Impact Damage - BVID) and that can compromise the residual structural resistance of the component, leading to catastrophic failures.

In addition to classical sources of Low Velocity Impact (LVI) damage, e.g. manufacturing, assembly, etc., ballast projection, or flying ballast, is a typical example concerning the railway field [15]. In general, an impacting object in the railway field is defined as any solid or debris surrounding the railway track that, due to mechanical and aerodynamic forces generated by train motion, can become airborne and can impact the vehicle with a velocity in the range between 1 and 10 m/s with consequent damage of structural parts [9,15–17].

As a consequence, finding mitigation actions for this kind of random events plays a fundamental role for the developing of new applications of composite materials in railways industry. For this purpose, in this work the advantages obtained by shifting the excellent TPU mechanical properties to composite components are investigated, in order to improve their impact resistance and enhance the safety of the vehicle.

At first, tests were performed to characterise the TPU and to evaluate its compatibility with the manufacturing techniques of the traditional composite laminate; successively, an extensive test campaign has been carried out at different impact energy levels to evaluate the impact resistance of hybrid TPU/CFRP laminate, and the results were compared with traditional laminates. NDT techniques were used to measure the extent of the internal damage in order to analyse the effect of the polymeric coating on the dissipation mechanisms of the energy during the impact event.

2. Thermoplastic Polyurethane

Thermoplastic polyurethane (TPU) belongs to elastomers family that joins the mechanical properties of rubbers with the manufacturing capability of thermoplastic polymers. Thermoplastic polyurethane (TPU) is formed by linear segmented block copolymers having soft amorphous segments (SS) and hard crystalline segments (HS). Soft segments are made of long flexible polyether or polyester chains that links two hard segments, which are, in turn, made of diisocynate. The latter segments, interconnected by hydrogen bonds, act as multifunctional tie points that form a non-covalent physical crosslink. The soft segments, instead, form an elastomers matrix, which is responsible for TPU elastic properties [17].

2.1 TPU coated CFRP

In order to improve the impact energy absorption of CFRP, rather than using TPU as matrix [18], or as an interleaved layer in form of sheets or veils [19,20], in this work an elastomer coating solution was chosen to be applied on the CFRP surface where the impact event takes place. In this work, a blend of TPU and natural rubber (NR) is used as coating layer. This kind of blend (NR-TPU) gained attention due to the combination of its good mechanical properties (good strength and high strain at failure, low temperature dependence, good damping characteristics and abrasion resistance [21]), the low processing costs, and their green, environmental friendly behaviour given by the natural rubber (NR) compound.

In this work, the blend of natural rubber and thermoplastic polyurethane is defined with the notation "TPU".

3. Materials and Samples Manufacturing

The natural rubber thermoplastic polyurethane used to hybridise the CFRP samples was obtained from a 3700 x 686 x 1 mm sheet with a 55A shore hardness. The properties of the material are illustrated in Table1.

Table 1. 55A SH TPU Properties.

Property	Unit	55
100% Modulus	MN/m^2	1.7
300% Modulus	MN/m^2	3.1
Tensile Strength	MN/m^2	25
Elongation at Break	%	680
Angle Tear Strength	KN/m	34
Compression Set	%	25
Resilience	%	55
Abrasion Loss	mm^3	<30

The material used to manufacture the CFRP laminate was a carbon fibres reinforced pre-preg CYCOM 977-2 epoxy system. Specimens were fabricated using a cross ply staking sequence of 11 plies, $[0/90/0/90/0/\overline{90}]_s$ and cut with the dimensions of 150 mm x 100 mm. TPU coating was carried out by the direct application of the thermoplastic polymer (sheet of 150mm x 100 mm) on the uncured laminated material. Afterwards, using an optimised cure cycle, the samples (Fig. 1) were cured in autoclave at 100 Psi and 120°C for 8h.

The optimisation cycle was carried out considering that TPU starts to degrade at 150 °C with potential manufacturing issues during the standard cure cycle of the pre-preg material (180°C for 3h). Consequently, a cure time of 8h was determined via numerical interpolation considering the standard cure cycle and setting the cure temperature at 120°C.

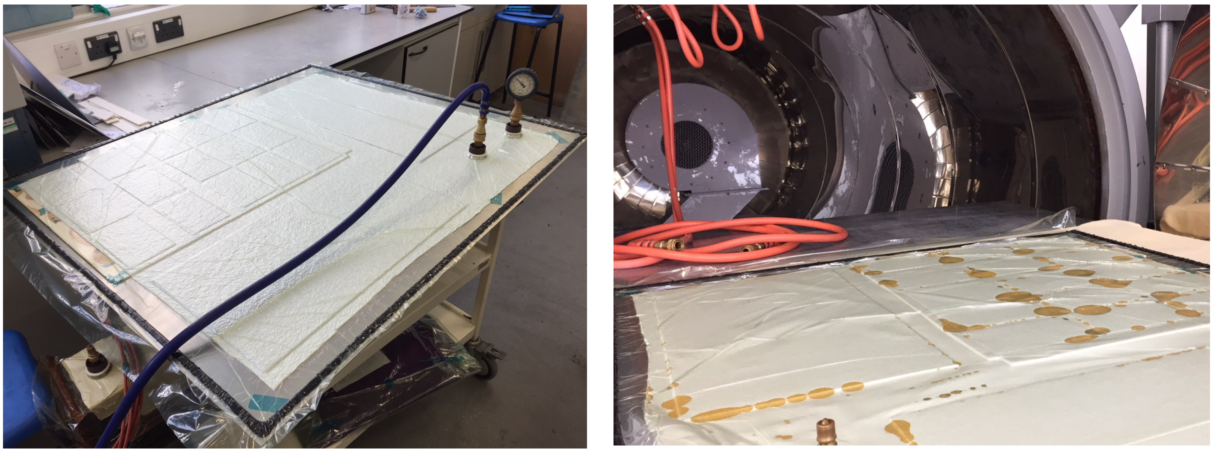


Figure 1. Sample manufacturing process: vacuum bag (left) and autoclave curing (right).

4. Experimental Tests

4.1 Low Velocity Impact Test

In order to investigate the effect of the superficial TPU coating on the impact properties of the hybrid laminates, Low-Velocity Impact (LVI) tests were carried out on TPU coated and reference CFRP samples, with two different energy levels: 2 – 3 J. These two energy levels were chosen to evaluate the limits of BVID inspection, representing a typical range of energies for common causes of visually undetectable damage due to impact phenomena or tool drop.

Impact data were collected using a Kistler Accelerometer and output results were elaborated by a MATLAB® script giving in output Force vs. Displacement curves. Impact tests were performed following the BS EN ISO6603-1:2000 and BS EN ISO6603-2:2001 standards. Specimen thickness of all tested laminates was between 2.00 mm (w/o TPU) and 2.8 mm (w TPU). The impactor apparatus (see Figure 2) used in the experimental campaign is a dropping tower unit, (2.66 kg shuttle weight). The samples were placed into the impact machine using a dedicated clamping support to apply the appropriate constrain conditions and avoid undesired vibrations.

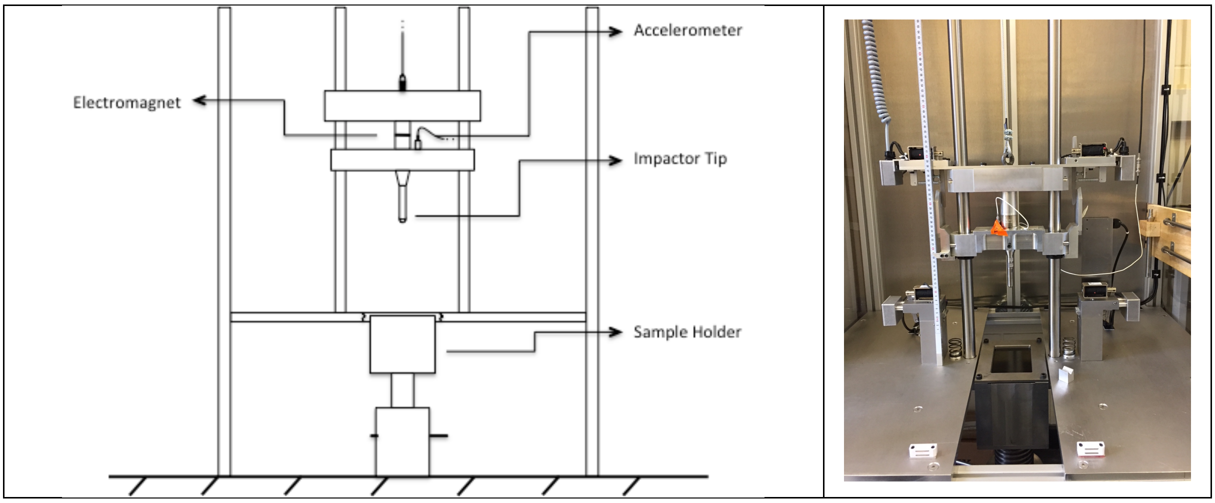


Figure 2. Impactor: scheme (left) and detail (right).

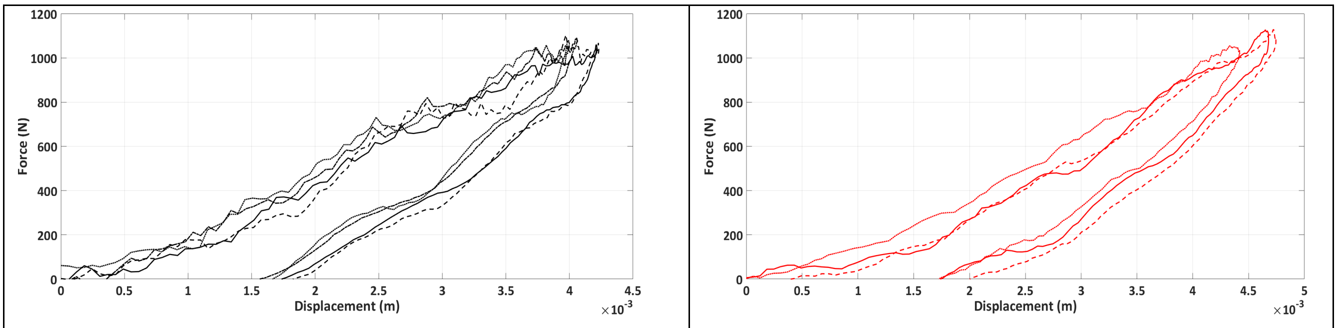
4.2 NDT – Phased array

The planar extent of the internal post-impact damage was investigated through a 5MHz Phased Array Transducer at 128 Channels (National Instrument) in order to estimate the location of the impact damage and its maximum diameter. Images show in-plane amplitude variation in a colour-map scale (from 0 to 75 V) which displays damaged areas in red for the maximum value and white for the minimum. Both experimental configurations (TPU-coated and reference) were analysed following this methodology.

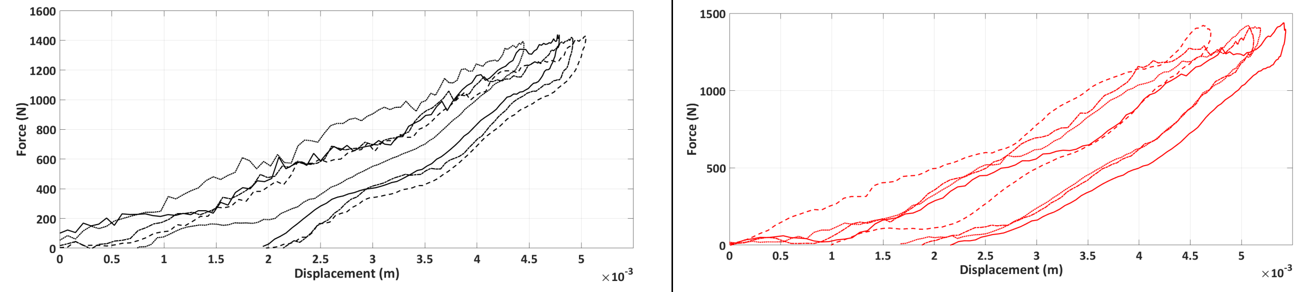
5. Results and Discussion

5.1 Low Velocity Impact

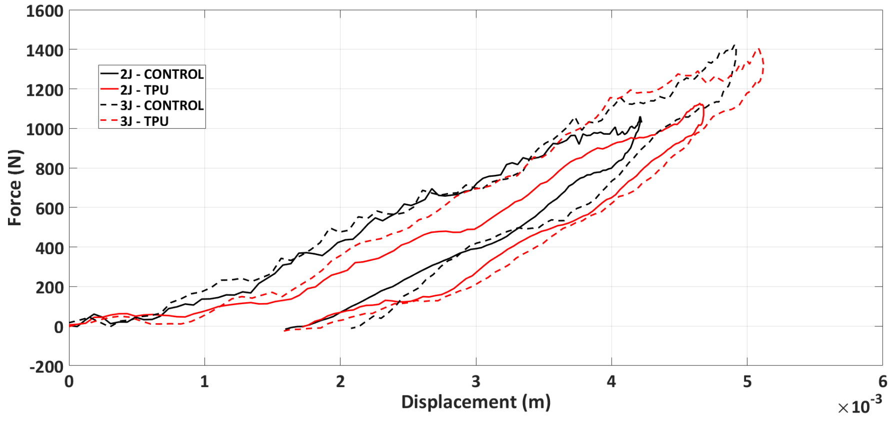
In order to demonstrate the damage suppression ability of TPU-coated samples, an experimental impact campaign was carried out at different energy levels. Control samples (without TPU coating) were impacted at same energy levels as the baseline material. Output data obtained from the LVI tests are reported in (Fig. 3) which shows all the collected Force-Displacement curves and the comparison between control and hybrid laminates.



a) 2J - CONTROL **b) 2J - TPU**



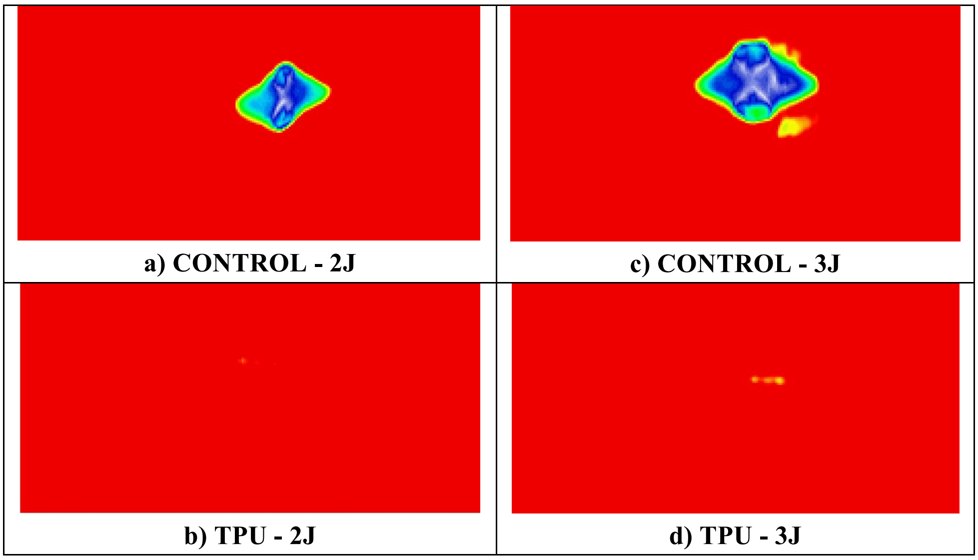
c) 3J - CONTROL **d) 3J - TPU**



e)

Figure 3. Force Displacement curves obtained from impact tests: a) control samples impacted at 2J, b) TPU samples impacted at 2J, c) control samples impacted at 3J, d) TPU samples impacted at 3J and e) comparison between different curves for control and TPU samples at different energies.

Post-impact phased array tests were carried out on the sample in order to investigate the eventual inner damaged areas generated by the impact event and the results are illustrated in (Fig. 4). Images were collected from the bottom surface, opposite to the impact location.



a) CONTROL - 2J
c) CONTROL - 3J
b) TPU - 2J
d) TPU - 3J

Figure 4. Phased-array damage detection images from the impacted sample in 16 bit colour-map scale: a) control sample impacted at 2J; b) TPU sample impacted at 2J; c) control sample impacted at 3J; d) TPU sample impacted at 3J.

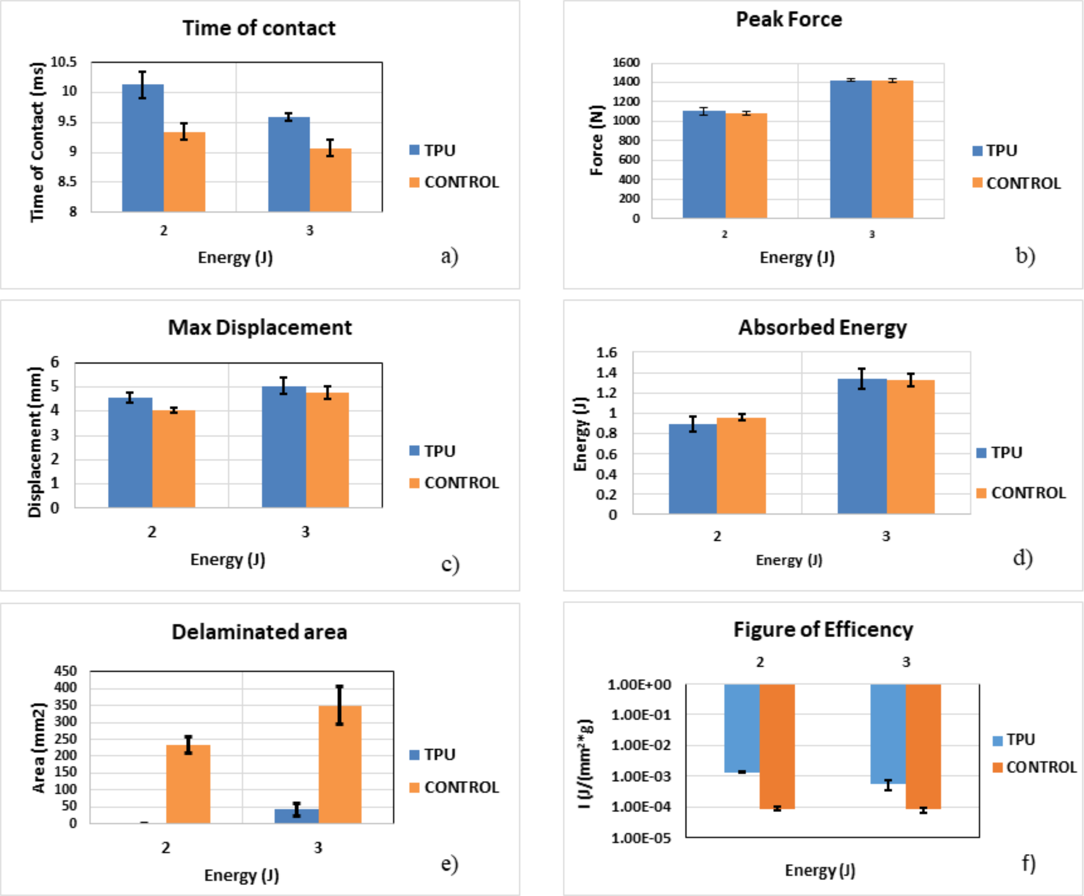


Figure 5. Statistical data charts on impacted samples at 2J and 3J for TPU and baseline samples: a) time of contact, b) maximum contact force, c) maximum displacement, d) absorbed energy, e) delamination extension and f) figure of efficiency in logarithmic scale.

As it is possible to see from all the output data, the use of TPU polymer as coating for CFRP plates gives several benefits against LVI damage. In particular, considering Figure 5.a and Figure 5.c, it is evident how the presence of the TPU layer increases the time of contact and maximum displacement recorded during the impact in comparison with the control configuration by +8.34% and +12.58% for the 2J and +5.66% and +5.44% for the 3J impacts.

Moreover, as shown in Figure 5.b, the values of force peaks are not affected by the presence of TPU and the impact responses are the same even at different energy levels with a variation of only +1.85% and -0.08% respectively for 2J and 3J between the TPU coated samples and the baseline.

It is important to observe from Figure 5.d that, for both the hybrid and the control samples, the energy absorbed during the impacts is very similar for both the energetic levels with just a difference of +7.26% and +0.35% for the 2J and 3J impacts respectively. Although this result seems in contrast with the main objective of this experimental work, in order to fully understand the different mechanisms with which the energy is absorbed during the impact event, these data need to be put in relation with the extent of the internal post-impact damaged area (see Figure 5.e) observed for both the hybrid laminate and the baseline. Indeed, analysing these results, it is possible to observe that for the same absorbed energy, the control samples show a greater damaged area than TPU samples (+100% for the 2J impacts and +88.23% for the 3J impact). Regarding the observed small damaged area for the hybrid material at 3J it must also be taken into consideration that these are mostly located at the interface between the polymeric layer and the laminate, therefore there is no damage within the structural part of the sample.

In order to understand this change in behaviour, it is important to understand how the energy from the impactor's head is transferred to the sample during an impact event. Indeed, for LVI impacts, when no perforation is reported, the impact energy is totally transferred to the sample in the indentation point. Part of this energy will be stored into the material as elastic energy (E_{el}) and transferred back to the penetrator, while another fraction will be absorbed (E_{ab}) by the system [22–24]. Thus, for the energy conservation balance it is possible to write:

$$E = E_{ab} + E_{el}. \tag{1}$$

E_{ab} can be further divided into three parts: E_d which represents the energy used to create damage (delamination, fibre brakeage and matrix failure) when the energy transferred to the sample exceeds the elastic threshold, E_v that represents the energy absorbed by vibrations via damping mechanisms [25] and E_M which includes all the other system dissipative components such as heat, the inelastic behaviour of penetrator and supports, and other non-linear behaviours.

Thus, the balance can be written as:

$$E = E_{el} + E_d + E_v + E_M \tag{2}$$

In the case of traditional CFRP, the sample is able to dissipate impact energy via the creation of new surfaces between two subsequent plies (delamination) at different orientation due to its laminated nature [26]. This leads to have a considerable amount of energy E_d absorbed by the system. On the contrary, when a layer of TPU is added as coating to the traditional CFRP, the hybrid system is able to store more energy into the E_{el} term since the TPU shows a lower stiffness than CFRP and higher elastic energy accumulation before failure (higher strain at failure). In addition, due to higher damping properties [27], the polymeric coating is able to absorb a larger amount of shock waves, allowing to transfer even more energy from the E_d into the E_v term. As a consequence, exploiting both the damping ability and the higher strain at failure of the TPU, the hybrid laminate is able to transfer most of the E_d energetic term into the terms E_{el} and E_v leading to a system which is able to absorb the same amount of energy of a traditional laminate with no sign of internal damage.

At this point, it is important to consider that the presence of the TPU negatively affects both the thickness of the laminate and its total weight. Therefore, to correctly evaluate the efficiency of the TPU/CFRP system in terms of energy absorbed it is necessary to take into account these variations by defining a figure of efficiency (I) which can be defined as:

$$I = \left| \frac{E}{W(1-A)} \right| \tag{3}$$

where E [J] is the energy absorbed during the impact event obtained by the accelerometer, A [mm^2] is the damaged area extension measured from the phased array images and W [g] is the weight of the sample. High index values correspond to a higher efficiency in terms of dynamic response (vibration damping and maximum displacement) and damage protection (reduction of delaminated area) against LVI events. The statistical data for this index are reported Figure 5.f for both configurations and for each level of energy.

Analysing the data, it is clear how, even considering the increased weight of the TPU laminate, the benefits obtained from the coating are still valid and useful to prevent damage from LVI events. As it is possible to see from Figure 5.f, for the 2J the efficiency increases by two orders of magnitude (+1481%) when the TPU is added to the CFRP laminate, and a similar trend can be observed also for the 3J impacts (+600%).

6. Conclusions

This research studied the benefit of a Natural Rubber - Thermoplastic Polyurethane blend coating applied on the impact surface of Carbon Fibre Reinforced Polymer laminate. The main objective was to evaluate the effect of the presence of the TPU layer on the energy absorption of the structure and study the reduction of damaged areas under LVI conditions. Following the ISO standard and using a drop tower machine, TPU-coated samples were manufactured and impacted with a range of energies required to inflict Barely Visible Impact Damage (BVID), simulating the kind of damage that can be generated by the collision with random airborne debris (e.g. flying ballast) or caused by accident during manufacturing process and maintenance procedures (i.e. dropping tools). Analysing the results, it is possible to observe that the polymeric layer is capable to convert the applied impact energy into elastic and damping energies with no sign of damage inside the structural part (CFRP) of the coated laminate. This results in an increased time of contact (at least 4.10%), maximum displacement (at least 5%) but similar force peak and absorbed energy (in comparison with a traditional CFRP).

In order to evaluate the total efficiency of the TPU/CFRP hybrid system in response to an impact event, a figure of efficiency was defined taking into account the absorbed energy, the weight increase given by the polymeric coating and the extent of the internal delaminated area. From these data, even if the weight is increased, an increase of the figure of efficiency value of at least +600% is observed and a convenient protection action by the TPU-coating is reported.

The results obtained by this experimental campaign proved that TPU coated CFRP laminates are able to absorb impact energy without the generation of internal damage. As a consequence, the use of polymeric coatings can constitute a viable solution to mitigate detriment caused by typical impact phenomena in railway applications (caused by ballast, grits, ice, leafage) improving impact resistance, and therefore extending the use of composite materials into railways applications, enhancing the reliability and safety of the vehicles.

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