Thermosetting and thermoplastic impact attenuator under axial loading

THERMOSETTING AND THERMOPLASTIC IMPACT ATTENUATOR UNDER AXIAL LOADING

S. Boria[1], G. Belingardi[2], A. Scattina[2]

[1]School of Science and Technology, University of Camerino, 9 Madonna delle Carceri, Camerino, Italy
[2]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, 24 Duca degli Abruzzi, Torino, Italy

Corresponding author:
Simonetta Boria
Email: simonetta.boria@unicam.it
Tel.: +39 0737402503

ORCID:
Simonetta Boria: 0000-0003-2073-4012
Giovanni Belingardi: 0000-0003-1378-1902
Alessandro Scattina: 0000-0001-8035-7488

ABSTRACT

High performance composites are generally fabricated with continuous fibre and fabric reinforcements embedded in a thermosetting resin. By using thermoplastic matrices there are substantial reductions in forming time and labour. More recently, the availability of all-polypropylene (PP) composites, achieved by using the same thermoplastic polymer for both the fibre and the matrix phase, are increasing thanks also to their recyclability.
In this perspective, the work is aimed to study the mechanical behavior of a new fully thermoplastic composite, first showing the results of an experimental campaign for the mechanical characterization of the material properties, then examining the behaviour of structures made of such material under axial loading in order to evaluate their energy absorption capability. This second part of the work is divided in two steps. In the first step crush tests on simple tubes were performed. In the second step the behaviour of a specific impact attenuator for a Formula SAE racing car was analysed. Using the same geometry, different material solutions were tested. Beside traditional thermosetting composite structure, a new fully thermoplastic composite and a hybrid solution were used taking into account various feasibility problems in the manufacturing phases. Even if the thermoplastic attenuator does not exhibit the same absorption capability of the thermosetting solutions, an interesting crushing mechanism was noticed: no more brittle failure with formation of debris, but a ductile progression with a load distribution very close to an ideal absorber.

Keywords: axial crushing; energy absorption; impact attenuator; laminated thermoplastic composite; experimental tests

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1. INTRODUCTION

Today there are three main guidelines in the automotive design. The first one is the weight reduction. In the last years there was a trend of growth in the weight of the new cars. This growth was due to the continuous request for safer vehicles and for higher number of accessories. However, it is well known as the emission of carbon dioxide (CO_2) produced by a vehicle is directly related to the fuel consumption of the vehicle and consequently the weight of the car. Moreover, the emissions regulations for the type approval of a new vehicle are always stricter in particular with regard to the CO_2. In the European Union (EU), current climate targets require a 60% reduction in transport emissions by 2050 [1]. A second important task in the automotive design is the material recyclability. According to the regulations for the type approval in the EU, the 85% in weight of the material of a new car has to be recyclable [2], at the end of life. This regulation has a heavy influence in the choice of the material for the different parts of a vehicle during the design phase. Last but not least, the passive safety of the vehicles in case of accident, with particular attention to the passengers and the pedestrians protection [3-6]. Standard vehicle body structures such as energy-absorbing frontal frame rails, bumpers, and beams for the hood support are optimized to reduce as much as possible the crash pulse, that is the acceleration history of the occupant compartment during a crash.

In this view frame, it is clear as the design of the new vehicle needs lightweight and recyclable materials with high energy absorption capability. To this aim, in the last years, composites in which both the matrix and the reinforcement are made of the same thermoplastic polymers are also emerging together with more traditional thermoset composites for structural applications in the automotive design [7]. The thermoplastic composites are characterized by low cost, low weight and easier and quicker manufacturing processes compared to the thermosetting ones. Moreover, they are excellent alternatives to glass and carbon reinforcements for composites from the structural and the environmental point of view.

The aim of this work is to study the energy absorption capability of impact attenuators for automotive applications made of different types of composites. Both thermoset and thermoplastic composites were considered in this work. Next to the structural solution originally developed with a thermosetting composite, previously analysed and tested [8-9], the adoption of a new fully thermoplastic material [10] and hybrid solutions made of the both types were considered. The study was carried out from an experimental point of view. The work is divided into different sections. At first, a mechanical characterization of the thermoplastic composite was carried out in order to identify the mechanical properties of this material. In the second part, the thermoplastic material was used to make simplified impact attenuators with cylindrical tube shape. The tubes were subjected to crush tests to analyse their energy absorption capability and their failure mechanisms. Finally, impact attenuators with truncated pyramid shape were studied. As mentioned before, these components were made of only thermoset or thermoplastic composite or combining both the materials in hybrid solutions [11].

2. MATERIAL

The experimental tests for the evaluation of the energy absorption capability were conducted both on thermosetting and thermoplastic structures, however the thermosetting material vales have been used for comparison, so the material mainly investigated in this work is the fully thermoplastic composite. The commercial name of this material is the PURE thermoplastic. This material is composed with three layers of polypropylene tapes, which correspond to a core and two external skins. The thickness of the core is higher than the thickness of the skins. The three layers are co-extruded in a single tape. Respect to the skins, the core is a highly oriented and high strength material with high modulus. The two external skins have a special formulation for their welding to the core during the co-extrusion. The final material is made using hot-press or continuous belt press. The manufacturing technology used for the production of the PURE thermoplastic is covered by a patent. If compared with the traditional sealing process, the manufacturing technology of the PURE has big advantages: it has a large sealing window (130-180 °C) without loss of material properties and a short cycle time at pressure of 20-30 bar. The PURE is produced in tapes. These tapes are woven into fabrics. The fabrics are sealed together to produce sheets of raw material. The final components in PURE are made by thermoforming starting from fabric or sheets.

Both the matrix and the reinforcement of the PURE composite are made up of the same base material, consequently the PURE components as well as the process waste are completely recyclable. From a mechanical point of view, the PURE shows high stiffness with a low density. Moreover, it has good impact resistance [12]. In particular, it shows a soft crush behaviour. This means that when it is subjected to impact loads, the material does not fail into splinters but it deforms in a ductile way.

As regards the thermosetting material examined in this work, it is a carbon fibre reinforced plastic (CFRP) prepreg GG200-DT120 where the epoxy resin content is about 40%. Such material presents cross-linking temperatures similar to PURE, but it requires longer period of polymerization with isotherms at low pressure (around 10 bar). Such aspect, as shown below, proves to be decisive in the lamination and compaction process reducing the capability of energy absorption. Respect to the thermoplastic material, as expected, it exhibits a brittle behaviour typical for the thermosetting solutions [13].

3. EXPERIMENTAL METHODS

3.1. STANDARD TESTS

A series of standard tests for the mechanical characterization of the PURE material properties were carried out at the Laboratory of the Department of Mechanical and Aerospace Engineering of the Politecnico di Torino. All the tests have been described in detail in the previous work of the authors [12]. Here only the main details are reported for a better comprehension of the present research. Tension, compression, shear and three points bending tests were performed according to the ASTM Standards D3039, D3410, D5379 and D790, respectively. These experimental tests were carried out in quasi static condition with a servo-hydraulic testing machine.

The tensile tests were performed on rectangular specimens (250×20×6.9 mm) in displacement control mode. Three different test velocities were used (0.1, 5, 100 mm/s). The longitudinal strain of the specimens was measured with a standard extensometer while the applied load and the crosshead displacement were measured at the same time with the transducers (respectively a load cell and a linear displacement transducer) of the testing machine. The tests were carried out up to the loss of the load-bearing capacity of the specimen.

The compression tests were performed on rectangular specimens (150×20×6.9 mm) at a constant velocity of 2 mm/min. The free distance, before the test, between the two clamping devices was set to 50 mm. The tests were carried out up to the loss of the load- bearing capacity of the specimen.

The three points bending tests were performed on the same specimens used for the tensile tests at a constant velocity of 2.85 mm/s. The span between the two supports was fixed to 107 mm according to the considered ASTM Standard.

The shear tests were performed according to the Iosipescu shear test. The specimens had a rectangular shape with V-notches in the middle. Thanks to a specific clamping device, a quasi-uniform shear-stress distribution is obtained in the middle of the cross-section of the specimen. The tests were performed at a constant velocity of 2 mm/min.

3.2. CRUSH TESTS ON TUBES

Crush tests on tubes made of PURE were performed to study the capability of energy absorption of this material [12]. The tubes had a circular cross section and a fixed length of 200 mm. Three different values of the external diameter (50, 80 and 100 mm) and of the wall thickness (2, 3 and 4 mm) were investigated according to a full factorial test plan, as summarized in Table 1. Two different axial loading conditions were considered: the tests were performed in quasi-static (5 mm/s) and dynamic conditions.

Table 1: Geometric characteristics of the tubular specimens.

# Specimen	Code	Inner diameter D_i [mm]	Wall thickness t [mm]
1	50_2	50	2
2	50_3	50	3
3	50_4	50	4
4	80_2	80	2
5	80_3	80	3
6	80_4	80	4
7	100_2	100	2
8	100_3	100	3
9	100_4	100	4

The tests in dynamic conditions were performed using a drop weight testing machine with an applied mass of 301 kg. The impact velocities were in the range 1.8÷2.8 m/s. The tube specimens were constrained at their lower base to avoid uncontrolled side slips in the first phases of the impact. The acceleration and the velocity of the drop mass were recorded. The collapse behaviour of the specimens was studied recording the deformation of the specimen during the impact with a high-speed camera.

3.3. CRUSH TESTS ON IMPACT ATTENUATOR

Having summarized the main results of the previous work , this section is dedicated to the main topic of the study: the impact attenuators such as those used for a Formula SAE racing car subjected to crush load [8] considering the use of different types of composite materials. The impact attenuators had a truncated pyramid structure. The geometry of this component was defined considering the aerodynamic, the mechanical constraints and the technical regulations for this type of vehicles. The cross section of the impact attenuator had rectangular shape. Two of the consecutive corners on the longer edge of the rectangle had round edges to reduce the stress concentration along the edges of the pyramid during the axial crushing. The truncated pyramid had parallel bases. The wall thickness of the structure was not constant along the axis of the pyramid. The walls of the pyramid were subdivided in three parts along the axis of the pyramid as shown in Figure 1. The front part of the attenuator, that has the lowest cross section (part 1 in the figure), had also the lowest thickness. The wall thickness was increased from the top to the bottom of the structure, considering the longitudinal axis (Figure 1). The part with the largest cross sections (part 3 in the figure) had also the largest thickness. The three values of the wall thickness used in this work were 1.68, 2.16 and 2.4 mm. The wall thickness was not constant to conceive a triggering system and consequently to obtain a progressive collapse with reduced force peaks.

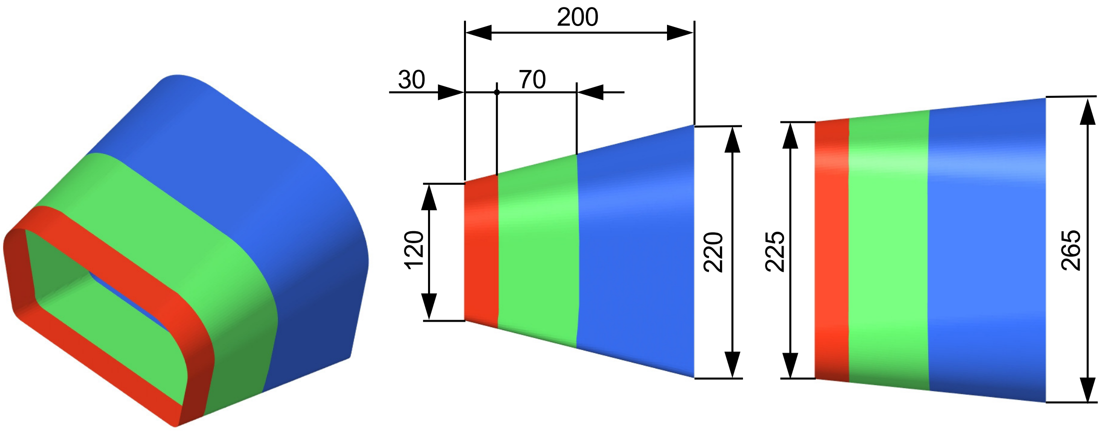

Figure 1: Geometrical configuration of the impact attenuator: iso view (a), side view (b), top view (c).

The impact attenuator made of CFRP was produced by hand lay-up starting from plain weave prepreg of carbon fibres and epoxy matrix [8]. The external part of the mould was made of epoxy resin to have dimensional stability at high temperature and chemical compatibility with the material of the attenuator. The mould was made starting from a block of resin and creating the shape of the attenuator using a milling machine and working in a conditioned environment. During the part manufacturing process, the mould was covered with vacuum plastic bag and was subjected to vacuum to avoid voids in the final component. The impact attenuators were obtained with an autoclave process. This type of impact attenuator was subjected to crush tests in quasi-static and dynamic conditions. The velocity of the crushing in quasi-static condition was fixed at 0.5 mm/s, whereas for the dynamic tests of impact, a drop mass of 301 kg was used. The impact velocity in this second condition was 7 m/s.

The attenuators made using the PURE were produced with four different stacking sequences (Figure 2). A first type was made completely in PURE (Figure 2-a). Even if the same material was used for all the layers, an alternate use of yellow and black lines in the Figure was adopted to identify more clearly the different layers. Four specimens of such configuration were tested and they were labelled as N_P_1-4. For the other attenuators hybrid solutions were adopted. In particular, in the second type the stacking sequence was made by alternating one layer of carbon fabric in epoxy resin with one layer of PURE (Figure 2-b). This type of specimen was identified with the label N_CP_1. In the third solution, a sandwich configuration was adopted where the core is made of PURE and the skins are made with CFRP layers (Figure 2-c). In such case this type of specimen was labelled as N_CP_2. In the last solution, the sandwich approach was used again but in this case the PURE was precured (Figure 2-d). Moreover, because of the withdraw of the edges of PURE layers during the curing process, in order to recover these structure voids, withdraw was compensated by addition of carbon layers, at both extremities. The label of this type of specimen was N_CP_3. As regards the manufacturing process a different methodology was used for the production of the hybrid attenuators compared to the CFRP structure. For the hybrid attenuators the mould in aluminium was the internal part of the impact attenuator (Figure 3-a), while a counter in CFRP was used for the external part in order to avoid wrinkles on the specimens (Figure 3-b). The presence of the steps on the surface of the attenuators visible in Figure 4 was due to the change into wall thickness in the three zones, as for CFRP impact attenuator.

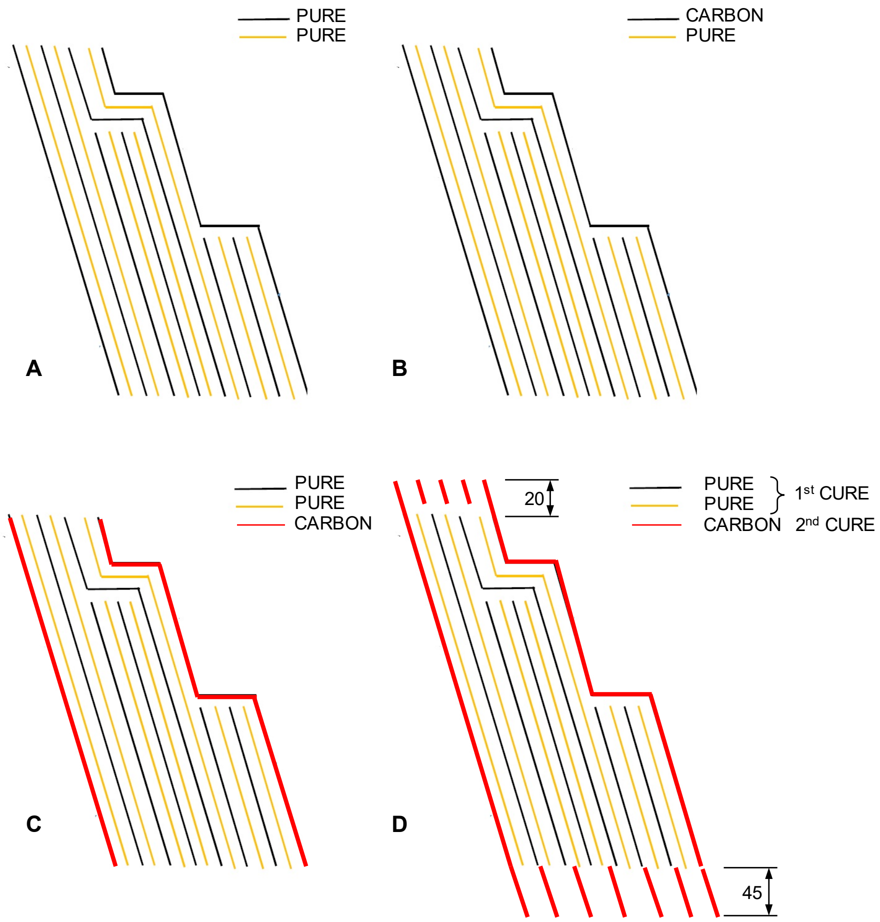

Figure 2: Different stacking sequences of the impact attenuators: a) only PURE (different layers made of the same material), b) PURE and CFRP alternatively, c) PURE as the core (different layers made of the same material) and CFRP as the skins, d) precured PURE as the core (different layers made of the same material) and CFRP as the skins and at the upper and lower edges.

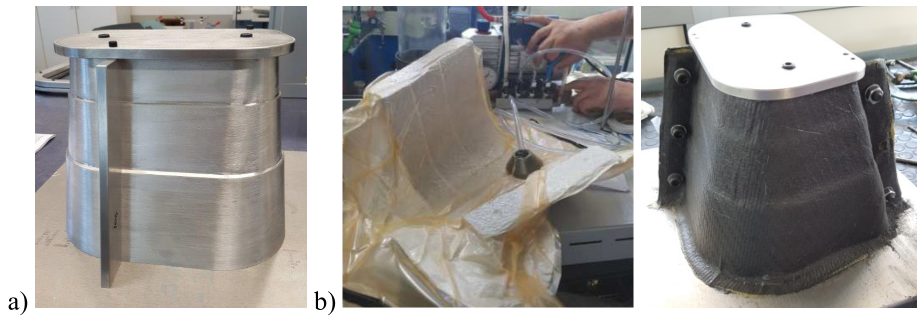

Figure 3: Mould (a) and counter mould (b) used for the manufacturing of the PURE and hybrid specimens.

4. RESULTS AND DISCUSSIONS

4.1. STANDARD TESTS

In this section the results obtained with the standard tests carried out on the PURE material are briefly reported and discussed, because they are useful for the analysis of the impact attenuator crush tests. The complete analysis of the results are reported in [12].

As regards the tensile tests, there was a strong influence of the test velocity on the mechanical properties of the material. As it happens for metals or plastic materials, increasing the test velocity the material showed hardening effects. In more details, there was an increase of the elastic modulus and of the tensile strength with the test velocity. Opposite behaviour was observed for the strain at failure. The failure of the specimens started with a detachment on the external skins. This specimen failure mode, in the authors opinion, may be explained by the fact that the material is probably affected by residual stress as a consequence of the manufacturing process [12].

As regards the compression tests, the failure of the specimens was due to a slip of the different layers of the fibres with a consequent delamination. The specimens showed a packaging effect of the fibres at the end of the test. The elastic modulus in compression was higher than the tensile one, whereas the compression strength was lower than the tensile one, as expected [12].

As regards the bending tests, the specimens were subjected to a first failure due to the detachment of the skin layer. This failure was located near the central span, where the load was applied. There was a drop in the load supported by the specimens as a consequence of this failure. A further delamination happened in the core of the material. This second delamination was located on one side of the specimen. A further decrease of the load supported by the specimen was observed. The load was quite constant after these two main failure phenomena, due to the ductile properties of the material [12].

In the shear tests the specimens did not reach a failure but they showed a slip of the fibre layers with a consequent compaction of the layers near the centre of the notch. The load applied increased increasing the amount of the deformation, as a consequence of this particular deformation mechanism [12].

4.2. CRUSH TESTS ON TUBES

For all the tubular specimens made of PURE material subjected to the static and dynamic axial crushing the load-displacement curve was recorded. Consequently, the energy-displacement curve was obtained. The crush behaviour of the specimens was also studied evaluating some parameters: average crushing stress, total absorbed energy, specific energy absorbed (SEA), crush force efficiency (CFE) and the stroke efficiency (SE). A detailed analysis of the results obtained in the crush tests is reported in [12]. In the present paper the main results are summarized.

In both the quasi-static and the dynamic conditions, the PURE did not show a brittle behaviour under the crush load. The specimens deformed with a soft ductile behaviour without the creation of splinters. The specimens showed a non-regular buckling, characterized by the concertina and the diamond collapse mechanisms up to a certain value of the compression stroke. After this value, the tube collapsed with a side bending. This second deformation mechanism had lower absorption capability than the first ones. The bending behaviour is less evident in the dynamic testing conditions. The deformation mechanism of the tubes was influenced by the geometrical properties: the most regular energy absorption was obtained with the smallest diameter (50 mm) and the intermediate thickness (3 mm), as shown in Figure 4. Moreover, the results showed as increasing the wall thickness of the specimen or decreasing its inside diameter both the average crushing stress and the specific energy absorption increase with a linear trend considering the tests in quasi-static conditions. A polynomial of second order fitted better the results obtained in dynamic conditions. The capability of energy absorption was similar for the static and the dynamic conditions, despite the mechanical properties of the material were affected by the strain-rate effect. The deformation mechanism shown by all the tubes while absorbing the energy was a plastic buckling. This behaviour was a consequence of the flexible linear chain of the thermoplastic materials. This material structure was completely different from the structure of the thermoset materials. The viscoelasticity of the polymer controlled the creep properties in quasi-static conditions. There was not enough time for the motion of the chains of the material in dynamic conditions.

Figure 4: Final deformation of the specimen 50_3 under static axial crushing.

4.3. CRUSH TESTS ON IMPACT ATTENUATOR

The trend of the crushing load in both the quasi-static and dynamic tests for the impact attenuator made of CFRP is shown in Figure 5. It is possible to observe three main peaks in correspondence of the change in the wall thickness [9]. The results showed as, in order to reduce the force peaks, the differences in the ply thickness should be reduced as much as possible or even eliminated. The crushing energy was absorbed by the CFRP composite structure through a progressive brittle behaviour, with the debris formation, bending of the straighter wall during crushing and sharp breaks of the laminate both in static and dynamic conditions (Figure 6).

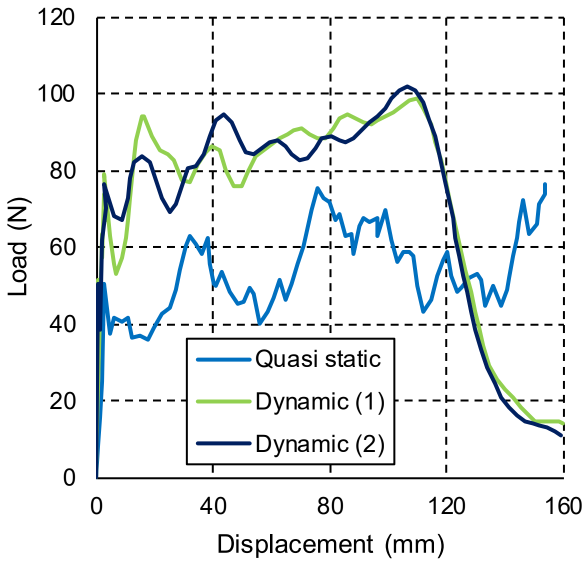

Figure 5: Force-displacement curves of CFRP impact attenuator in quasi static and dynamic crushing.

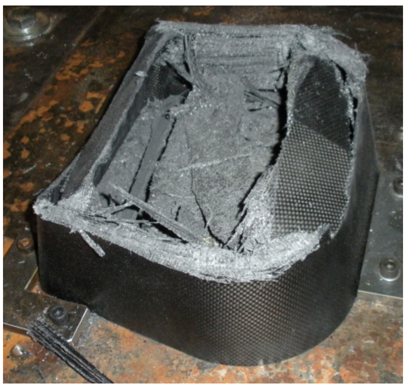

Figure 6: Deformation process of the CFRP impact attenuator: debris, bending and sharp break.

In Figure 7 the crushing behaviour of the impact attenuators made of PURE (N_P_1-4) is shown, whereas in Figure 8 there is the crushing sequence of the impact attenuators made of the hybrid PURE/CFRP material (N_CP_1-3). The attenuators with only PURE showed a ductile plastic behaviour during the crushing compared to the attenuators made of only CFRP composite material. The specimens with CFRP layers (N_CP_1-3) showed also a brittle behaviour for the layers in carbon, even if an elastic return was always present due to the behaviour of the thermoplastic material. As mentioned before, the different cure process between a thermoplastic and a thermoset solution, dictated by the temperature, pressure and time range, prevents a good level of compactions between the layers made of different materials. With the epoxy cure process, at temperatures between 135 °C and 180 °C, the withdrawal of the PURE cannot be controlled. For example, a plate measuring 400 mm × 500 mm, made of PURE, was reduced to a rectangle of 100 mm × 120 mm after the curing cycle at those high temperatures. The PURE thermoplastic fabric was proved suitable for a rapid molding process under press, without isotherms that are usually necessary for epoxies, and with pressures much greater than 10 bars. Such aspects implied a premature state of delamination with a consequent reduction of the energy absorption capability since the beginning of the crushing.

The results of the crushing tests in terms of load-displacement curves and energy-displacement curves are shown in Figure 9 and 10, respectively. The trend of the loads curves was quite scattered. However, it is possible to distinguish again a sensible load variation in correspondence of the change in the wall thickness. The load-displacement curve of the hybrid solutions showed a more regular behaviour compared to the specimens made only of PURE. With a good level of compaction between layers, the attenuators made only of PURE had better behavior than the hybrid configurations N_CP_1 and N_CP_2, where delamination was already present before the crushing. The hybrid solution N_CP_3 with the sandwich configuration, where the PURE was precured and the edges involved in PURE withdrawal were compensated with carbon layers, showed the best behaviour in

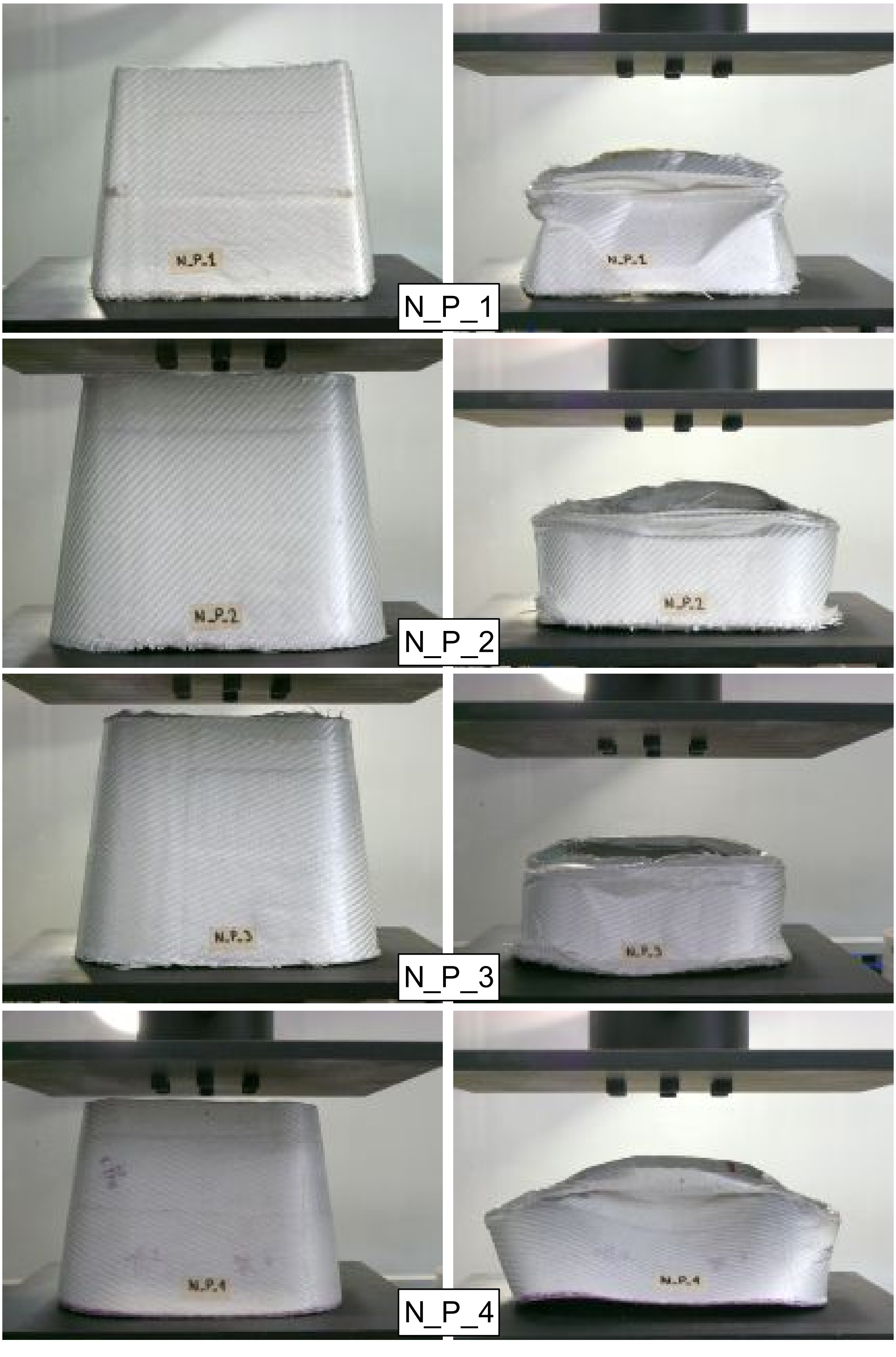

Figure 7: Crushing behaviour of the impact attenuators made of PURE: on the left-hand side the specimens before the tests, on the right-hand side the specimens after the tests.

terms of energy absorption capability. The value of the absorbed energy was much higher compared to the other types of specimens. The trend of its load curve showed a progressive increase whereas the curves obtained with the other specimens were more regular. Moreover, the hybrid configuration exhibited growth of the load during crushing whereas the load measured for the same attenuator in CFRP was quite constant. It is worth of note that the energy absorbed by the impact attenuators made of PURE have values of the same order of magnitude as the N_CP1 and N_CP_2 specimens.

Figure 8: Crushing behaviour of the impact attenuators made of hybrid solution: on the left-hand side the specimens before the tests, on the right-hand side the specimens after the tests.

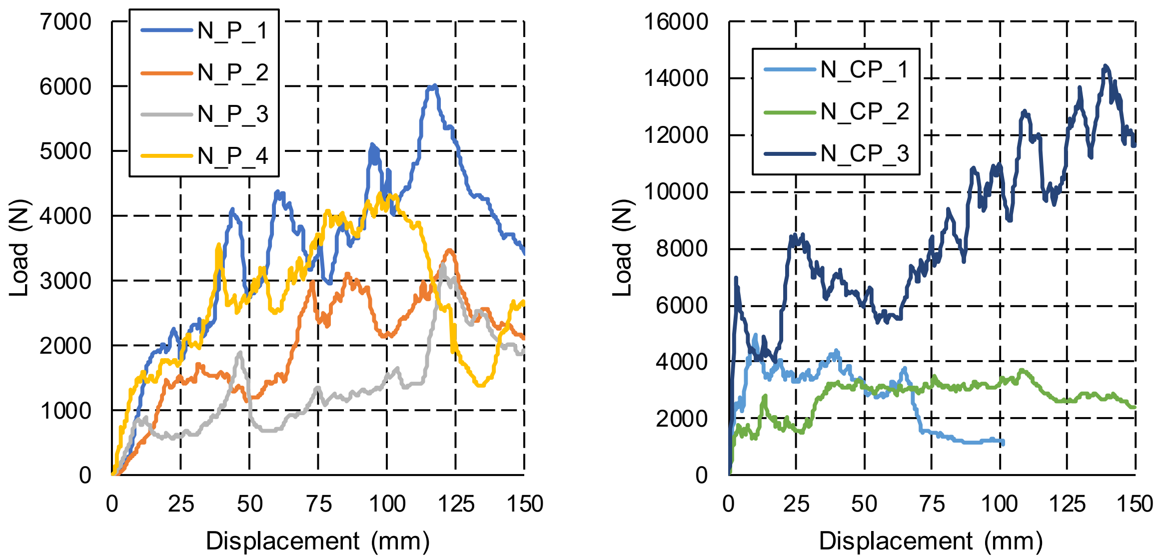

Figure 9: Load-displacement curves obtained in the crushing tests on the impact attenuators.

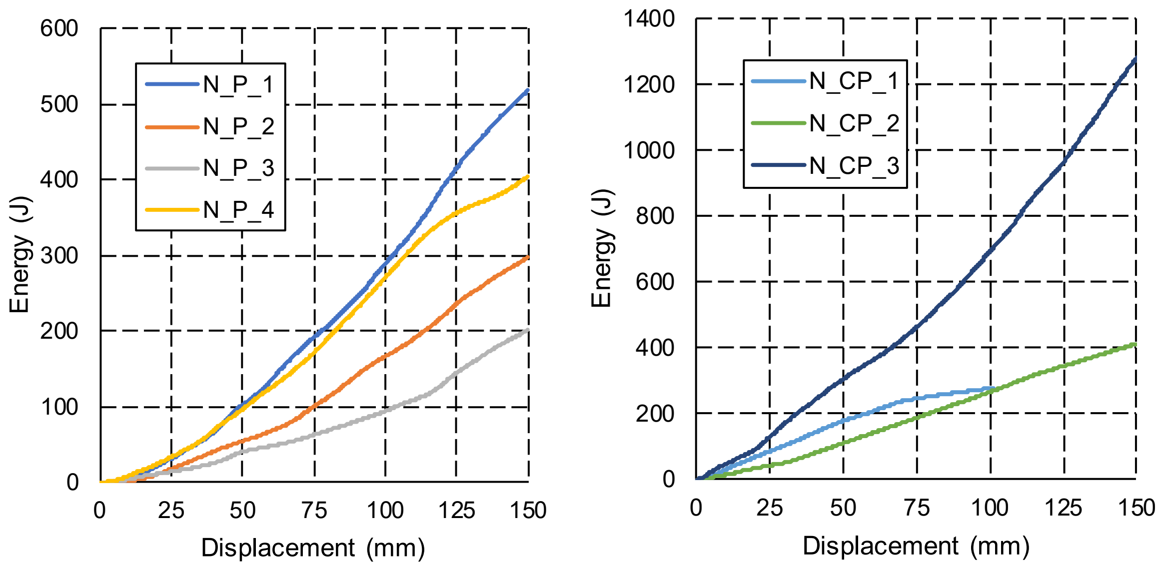

Figure 10: Absorbed energy-displacement curves obtained in the crushing tests on the impact attenuators.

5. CONCLUSIONS

Recently, the availability of all-PP composites, achieved by using the same thermoplastic polymer for both the fibre and the matrix phases, are increasing. In this work, the energy absorption capabilities of a new thermoplastic composite made of polypropylene (commercial name PURE) was carried out. The activity started with an experimental campaign done on the raw material. Subsequently, the axial crushing behaviour of cylindrical structures was studied with a series of experimental tests in quasi-static and dynamic loading conditions. The thermoplastic materials showed a crushing process between that obtained with a conventional metallic material and that obtained with a traditional composite material. A change in the deformation mechanism, passing from the typical folding to the global bending buckling, was observed in some cases, with a consequent loss in the load capacity of the specimen.
The crushing behaviour of the PURE thermoplastic composite is therefore interesting for applications where the use of lightweight and recyclable materials is fundamental such as in the automotive sector. With the PURE thermoplastic, it is possible to obtain a regular folding behaviour with a consequent high and regular energy

absorption like that obtained with a traditional metallic material. To get this behaviour a careful choice of the geometrical parameters of the structure is necessary.
Moreover, in this work, the PURE thermoplastic was used to produce more complex impact attenuators. Hybrid solutions between the PURE and the traditional thermosetting material were also considered. These two materials were not compatible from a chemical point of view, and thus the cure process was not completed. As a consequence, there were a lack of adhesion between the layers made of dissimilar material and therefore a loss of energy absorption capability. The PURE can be included within the class of thermoplastics suitable for the rapid process under press, with very high pressures and very short permanence at the sealing temperature.
Between the hybrid solutions taken into account in this work, the sandwich configuration, with the PURE for the core and the CFRP for the skins, appeared as the best one, even if particular care must be applied on the compaction level between the layers. The best solution in terms of progressive crushing and energy absorption capability was obtained with the attenuators produced in two steps. In the first step a precure of the PURE stacking sequence was applied. In the second step the laminate was covered internally and externally with CFRP layers. Moreover, the void edges created during the PURE withdrawal were filled with CFRP.

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