Experimental crushing analysis of thermoplastic and hybrid composites

EXPERIMENTAL CRUSHING ANALYSIS OF THERMOPLASTIC AND HYBRID COMPOSITES

S. Boria[1], G. Belingardi[2], D. Fiumarella[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:
Alessandro Scattina
Email: alessandro.scattina@polito.it
Tel.: +39 0110906900

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

ABSTRACT

In this work the mechanical properties of composites specimens made of thermosetting and thermoplastic materials are compared. The behaviour of a traditional carbon/epoxy laminate is compared with those of a fully polypropylene composite and of a hybrid composite. The hybrid composite is made by stacking different layers of thermoplastic and thermosetting material. The influence of different production processes, for the hybrid composite, are also investigated. The capability of energy absorption are investigated studying the crushing behaviour of impact attenuators. The impact attenuators made of carbon fibre reinforced plastic exhibit the highest load capability with the highest energy absorption. However, the failure mode is brittle with debris formation. Conversely, a failure mode of plastic crushing is observed in the structures made of fully polypropylene. The experimental tests on the specimen made of hybrid laminates proved a strong influence of the production process of the components on the mechanical properties. In the hybrid laminates, the different chemical properties of the base materials lead to a pre-existing delamination state in the final. The results highlight that curing the thermoplastic material before the compaction with the thermosetting laminates, is the best solution to guarantee the highest impact resistance.

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

EXPERIMENTAL CRUSHING ANALYSIS OF THERMOPLASTIC AND HYBRID COMPOSITES

1. INTRODUCTION

Safety, efficiency and recyclability are currently the guidelines for the design and the development of the new vehicle. Passive safety can be improved by minimizing the acceleration of the passenger compartment during an impact. To this aim, the crash pulse can be minimized using specific materials for the body structures that ensure a high degree of energy absorption [1-4]. Besides, these materials must guarantee a low weight and they have to be recyclable. It is well known that weight is strictly related to the fuel consumption. European regulations are becoming increasingly stringent regarding the CO_2 emissions. New directives state that by mid-century, greenhouse gas emissions from transport will be at least 60% lower than in 1990. To achieve this target, fleet-wide emissions for new type approval must not be higher of 95g/km from 2020 [5]. Finally, recyclability and material recovery must be considered. The actual directives for the type approval require the reuse and the recovery of the 95% of the weight of the vehicle: at least the 85% of weight of the materials of a new vehicle must be fully recyclable [6].

In recent decades, composite materials such as Carbon Fibre Reinforced Polymers (CFRP) were mostly developed, aiming to achieve a low weight of the structural components by guarantee a high impact safety.

However, the recycling of carbon fibres impregnated with resin presents a significant challenge. The majority of CFRPs are made using thermoset matrices, such as epoxy, that cannot be melted or reshaped after they are cured. Moreover, the manufacturing process of CFRP composite components is laborious and quite expensive. To meet these shortcomings, in recent years thermoplastic composite has been spread, offering advantages that promise to make this type of material one of the faster growing over the next decade. The upsides of thermoplastics have been well documented [7-10]. Topping the list is the fact that they are melt processed, which makes their pre-processing storage and handling easier to manage, particularly compared to pre-pregged thermosets, which require cold storage and limited out time. Thermoplastics are significantly easier to recycle, because they can be reheated and reformed, , therefore they have appeal across a number of end markets. Third, thermoplastics are typically processed out of the autoclave, which makes them energy and cycle-time friendly. Finally, thermoplastic materials, in general, offer greater toughness in the finished part than thermosets do, and some thermoplastic materials offer a higher end use temperature than the thermosets against which they compete, such as epoxies. Thermoplastics, however, are not without drawbacks. The first one is that the thermoplastic resins (polyether ether ketone-PEEK, Polyetherimide-PEI,) that provide the same strength as many thermosets do can be substantially more expensive. This is a hurdle in end markets, like automotive, that are more price sensitive. Still, thermoplastics' benefits are sufficiently attractive that they have become the subject of important research and development work over the last 5-10 years [11-13]. Despite the automotive industry has familiarity with the thermoplastics materials, the application of composites for structural components of cars and trucks has focused primarily on the use of thermosets, mainly epoxy [14]. Indeed, the first mass-produced vehicle using the carbon fibre composites for the body-in-white, the BMW i3, relies on a fast-cure (~5 minutes) epoxy developed by Huntsman Advanced Materials. Other epoxy suppliers, like Hexcel, Hexion, Dow Automotive and Cytec Solvay developed fast-cure epoxies for similar applications. However, the future might see higher use of thermoplastic composites, particularly due to the material recycling regulations. The most compelling technology of thermoplastic composite for automotive application came from carbon fibre manufacturer Teijin, which worked with General Motors to develop the Sereebo [15]. Data displayed by Teijin indicate that parts made with Sereebo exhibit also significant energy-absorption properties (70 J/g, compared to 59 J/g for continuous carbon fibre composites). More recently the spread of all-polypropylene (all-PP) thermoplastic composites, both in fibre and in matrix, can be also considered as an innovative and interesting solution for the automotive field, ensuring full recyclability, faster and simpler manufacturing processes than CFRP solutions together with low weight [16].

In this work the capabilities of energy absorption of a thermoplastic composite and of hybrid composite made of thermoplastic and thermoset laminas are studied. To this aim, experimental tests on impact attenuators are performed, considering the results obtained in previous tests and the analysis carried out by the authors [17-19]. The capability of energy absorption in case of impact is evaluated on a fully thermoplastic composite [20-22] and on hybrid solution in which the layers of CFRP material are alternated with the layers made of the fully thermoplastic composite.

The experimental tests carried out in this campaign are divided in two parts. First, the considered materials are characterized. The mechanical properties of the fully thermoplastic composite and of the hybrid composite are evaluated performing standard tests on specimens made of the two materials. The second part of the work deals with the study of the capability of energy absorption: experimental tests of crushing were carried out on impact attenuators with simplified geometry. The considered geometry is compatible with the geometry required for the impact attenuator of the formula SAE vehicles by the regulation [23]. The crushing tests were carried out both in quasi-static and dynamic conditions. The tested components were made of fully thermoplastic composites or of hybrid sheets made up of thermoset and thermoplastic composites [24]. A comparison between the results obtained with the two types of materials are discussed in the last section of the work.

2. MATERIALS and METHODS

2.1. MATERIALS

The inquired specimens and impact attenuators are made of two materials: a fully thermoplastic composite and a hybrid composite made up of layers of the thermoplastic composite and layers in thermosetting composite. Different stacking sequences were considered. The thermosetting material was a CFRP prepreg GG200T-DT120. The matrix was made of epoxy resin, and the content of the matrix was about the 40% in volume. The long polymerization time with isotherms at low pressure (10 bar) requested by the thermosetting material is a drawback compared to the more flexible production process of the thermoplastic composite. Moreover, the brittle failure mode when the thermosetting composites are subjected to load impacts is a limit in the capability of energy absorption of this material.

The thermoplastic composite was a fully polypropylene composite produced with a patented process. The commercial name of the material is the PURE© thermoplastic. It is basically made up of a polypropylene homopolymer and a polypropylene copolymer. The PURE© composite is produced in tapes made up of a core and two external skins. The tapes are obtained using a co-extrusion process followed by drawing and hot-compaction. The high oriented and high strength homopolymer is the core of the material, whereas the copolymer is used for the two skins. The two skin tapes have a lower melting temperature than the core and thus co-extrusion process can be applied. After that, the drawing and the hot-compaction provide good mechanical properties to the final sheet of composite. The PURE© tapes are then woven into balanced weave fabric (orientation [0°, 90°]), that are joined together producing sheets of raw material. The PURE© shows a softer behaviour when subjected to impact loads, due to its low density and high stiffness. During the propagation of the failure the material does not splinter, but a ductile response is observed. The high reinforcement volume fraction, the large sealing window (130-180 °C) and the short cycle time at pressure make PURE© a simple and flexible material to process. Furthermore, having both matrix and fibre composed by polypropylene, PURE© components as well as their process wastes are fully recyclable. All these features make this material suitable for the minimization of the cost-efficiency ratio, as requested, for example, by the automotive industry.

2.2. STANDARD TESTS ON PURE©

Tensile, compression, three-point bending, and shear tests were carried out on the thermoplastic material to define its mechanical properties. The specimens used for these tests were cut from a 600×1200 mm sheet by waterjet cut thanks to the poor permeability of the PURE©. The thickness of the specimens was the same for all the tests. An Instron 8801 servo-hydraulic testing machine located at the Mechanical and Aerospace Department of the Politecnico di Torino was used to execute the quasi-static tests, according to the ASTM standards D3039, D3410, D5379, D790.

For the tensile tests, nine rectangular specimens with dimensions 250×20×6.9 mm were tested in displacement control. The specimens were divided in three groups. Each group was tested with a different crosshead speed (0.1, 0.5, 100 mm/s). These values were defined to evaluate the sensitivity of

the material to the strain rate. An Instron 2620-604 dynamic extensometer was used to evaluate the longitudinal strain.
For the compression tests, rectangular specimens were also used. The width of the specimens was the same of the specimens used for the tensile tests whereas the length was reduced to 150 mm. The initial distance between the two fastening of the machine was fixed to 50 mm. Four specimens were tested in this loading condition imposing a constant velocity of 2 mm/min to the crosshead of the testing machine. The compression tests were carried out up to a loss of load carrying capacity.
The specimen geometry used for the three-point bending tests was the same of that used for the compression tests. According to the ASTM D790 standard, the crosshead velocity was fixed to 2.85 mm/min, and a span distance between the two supports of 107 mm was used.
Iosipescu standards for the shear tests were considered as guidelines to evaluate the shear properties of the material. According to the Iosipescu standards, the specimens were cut with a rectangular shape (76×20×6.9 mm) with two central V notches, one for each side. These tests were performed at a fixed velocity of 2 mm/min, using a specific clamping device aimed to obtain a quasi-uniform shear-stress distribution in the middle cross-section of the specimen.

2.3. STANDARD TESTS ON CFRP AND HYBRID SPECIMENS

Standard tests were also carried out on carbon and hybrid (carbon-PURE©) specimens to investigate the mechanical properties of the composite materials used to produce the impact attenuators. In the following the fully carbon specimens are identified with the label CC, whereas the hybrid carbon-PURE© specimens are identified with the label CP. Tensile and three-point bending tests were performed according to the previous listed ASTM standards using rectangular specimens with dimensions 175×20 mm. The specimens were obtained from larger sheets with water-jet cutting. The sheets were the same used for the production of the impact attenuators. Therefore, accordingly to what is discussed in section §2.4 each sheet was laminated with a variable thickness. In particular, it was possible to distinguish three different zone with three different thickness as shown in Figure 1A. The rectangular specimens where obtained cutting each part with a constant thickness, consequently specimens with three different thickness were obtained as reported in Table 1. For each of the considered thicknesses, three specimens were tested. The carbon-PURE© specimens were made by alternating layers of carbon and PURE© lamina as shown in Figure 1B. The specimens were named with the following label format:

XXT-#

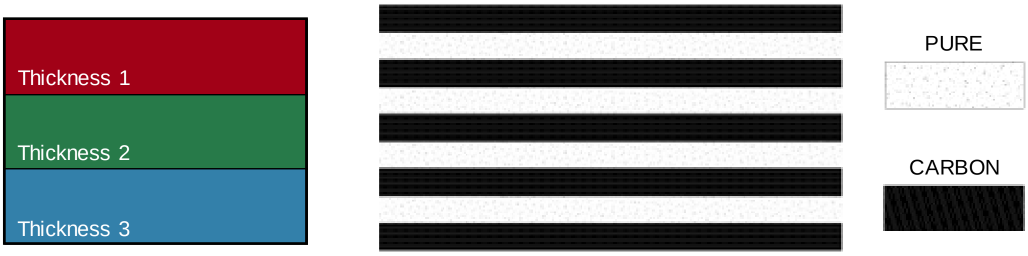
Where:
XX: material of the specimen

- CC: full carbon specimen
- CP: carbon-pure specimen

T: thickness of the specimen

- 1: lowest thickness
- 2: medium thickness
- 3: highest thickness

#: progressive number of the specimen
Both the tensile and the bending tests were carried out applying a constant velocity to the cross-head of the testing machine. The velocity was set to 2 mm/min. In the tensile tests the strain in the longitudinal and transversal direction were measured applying strain-gauges on one side of the specimen.
Concerning the three-point bending test, the test parameters were the same described in section 2.1. The support span distance was changed in function of the thickness of the specimen, according to the ASTM D706 Standard as detailed in Table 1. Both the tensile and the bending tests were carried out up to the loss of load capacity of the specimen.



(A) (B)

Figure 1: On the left-hand side (A) top view of the sheet used for the production of the specimens, on the right-hand side (B) example of the stacking sequence of the hybrid lamina used for the tensile and three-points bending specimens

Specimen label	Average thickness (mm)	Average span (mm)
CC1-#	1.60	27.2
CC2-#	2.43	34.4
CC3-#	3.48	55.5
CP1-#	1.25	25.4
CP2-#	1.88	31.1
CP3-#	2.42	41.2

Table 1: Specimens nomenclature, average thickness and testing span value for the carbon and the hybrid specimens used for the tensile and three-points bending tests.

2.4. CRUSH TESTS ON IMPACT ATTENUATOR

The impact attenuators considered in this work had a truncated-cone shape (Figure 2). The cross section of the cone is not a circle but a rectangle with two rounded corners to avoid stress concentration during the impact. The larger base had a width of 265 mm and is parallel to the smaller base that had a width of 255 mm. The thickness of the component was non-constant along the longitudinal axis (*x* axis) in order to reduce force peaks and to obtain a progressive collapse during the crush. The thickness of the attenuator along the longitudinal axis had three different values. Referring to the Figure 2, the red area is the front part of the attenuator and it had the smaller cross section. This part had also the smaller thickness (1.68 mm). The wall thickness of the attenuator increases from the front part to the rear part (the blue area shown in the Figure 2). Therefore, the green central part had a thickness of 2.16 mm and the blue part with the higher cross section, had a wall thickness of 2.4 mm. The considered geometry is compatible with the requirements of the technical regulations of the racing vehicles for the Formula SAE competitions [23]. . In these vehicles the impact attenuator is a deformable device located in the front part of the frame and it is aimed to absorb the energy of the vehicle during a front impact.
Three different material compositions were used to produce the attenuators subjected to the crushing testes. The three materials were the fully carbon fibre with epoxy resin [17], the fully PURE© and the hybrid composite made up of layers of carbon fibre in sequence with layers of PURE©.
The full carbon attenuators were produced with the hand lay-up technique using epoxy resin as matrix and plain-woven carbon fibres as reinforcement. The external part of the mould was made of epoxy resin in order to have chemical compatibility with the attenuator, to avoid geometrical inaccuracy due to the high temperatures, and to ensure the polymer sticking. The mould was machined with a milling process, obtaining the attenuator shape. The mould surface was covered with a plastic layer in which the vacuum was created, to enhance the surface finish of the component. An autoclave process was finally executed to complete the cure process and to obtain the final attenuator. Considering the carbon-PURE© attenuators, the internal mould was made of aluminium (Figure 3), whereas the external mould was made of carbon fibre to increase the surface finishing and to avoid wrinkles.

Quasi-static and dynamic crush tests were carried out on the attenuator made of fully carbon whereas only quasi-static tests were carried out on the other attenuators (fully PP and hybrid composite) . The quasi-static tests were performed using a Zwick Z100 electro-mechanical machine for universal tension-compression tests. The dynamic tests were performed using a drop dart equipment. The quasi-static tests were performed with a fixed crushing velocity of 0.5 mm/s. The dynamic impact tests were executed using a drop mass of 301 kg. The impact velocity was set to 7 m/s. In both tests, the crushing load was applied along the longitudinal axis (*x* axis) of the specimens, impacting on the side with the smaller cross section.

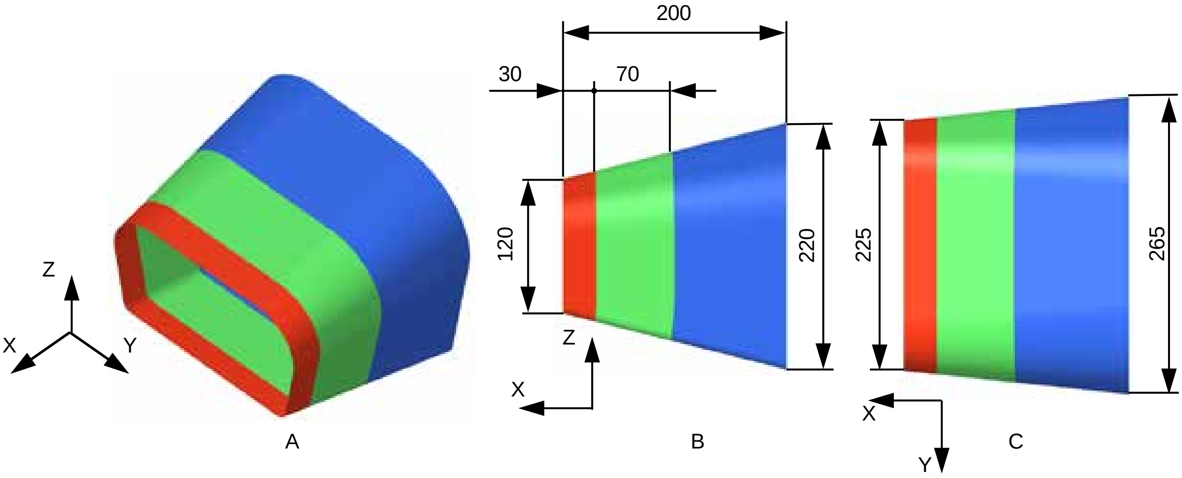


Figure 2: Geometrical characteristics of the impact attenuator: iso view (A), side view (B), top view (C).

Four specimens made completely of PURE© were tested. The stacking sequence of these attenuators is shown in Figure 4A. These specimens were labelled N_P_1-4. For what concerns the specimens made of the hybrid composite, three different stacking sequences were considered. The first staking sequence (labelled N_CP_1, shown in Figure 4B) was made up of alternating layers of CPRF and one layer of PURE©. The second stacking sequence (labelled N_CP_2, shown in Figure 4C) was made with a sequence of layers made of PURE©. A layer of carbon tissue was applied on the external and the internal surface of the attenuator. In this way a structure like a sandwich was created. The core was made of PURE© layers and it was enclosed between two carbon fibre skins. The third stacking sequence (labelled N_CP_3, shown in Figure 4D) was the same as N_CP_2. However, in this case, the PURE© layers were pre-cured. The curing process was suggested by the different chemical and physical properties of the two composites. Furthermore, in this last configuration, the edges on the two free cross section were covered with carbon layers in order to avoid voids due to the PURE© withdrawal.

(A) (B) (B)

Figure 3: Mould (A) and counter mould (B) used for the manufacturing of the PURE© and the hybrid attenuators.

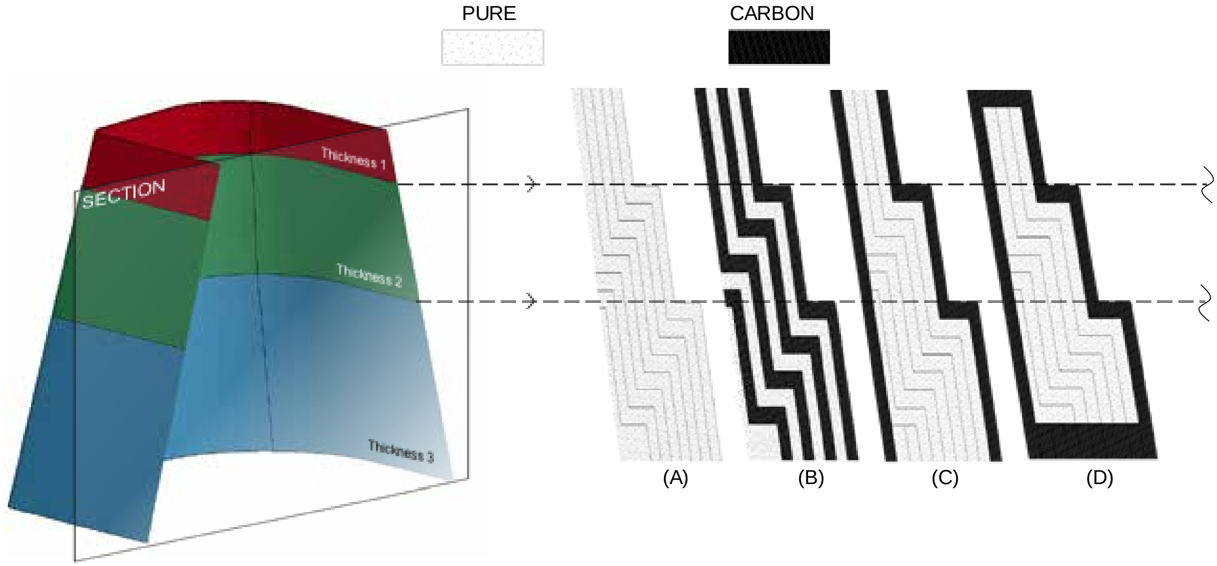


Figure 4: Different stacking configurations of the impact attenuators subjected to crush tests: (A) fully PURE© (different layers composed by the same material); (B) alternating layers of PURE© and CFRP layers; (C) sandwich configuration (PURE© on the core and CFRP as external skins); (D) sandwich configuration with precured PURE© and CFRP as external skins and on the edges.

3. RESULTS AND DISCUSSIONS

3.1. STANDARD TESTS ON PURE

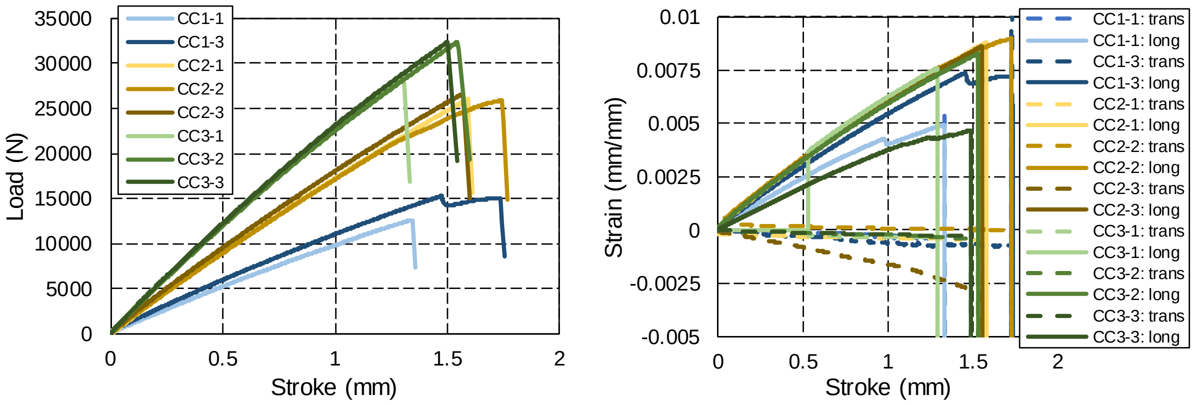
The results of the tensile tests made on the PURE© specimens were reported by the authors in [25]. The results showed relationship between the test velocity and the mechanical properties. As expected, being a thermoplastic material, there was an increase of the elastic modulus increasing the test velocity. In opposite, higher the test velocity, lower the maximum strain to failure. The first failure of the specimen was found on the outermost layer of fibres. This behaviour was a consequence of the residual stresses due to the production process. After the first failure on the side layer, an alternating of delamination and relaxation was observed in the core fibres. Consequently, a decrease in the elastic modulus was observed.
The specimens tested in compression showed an elastic modulus higher than those obtained in the tensile tests. The maximum load and the strain to failure were much lower. The loss in the load capacity was due to a sliding of the different layers of fibres caused by delamination phenomena.
The behaviour of the specimens showed during the bending test can be divided in three steps. The first increase of the load generated a delamination of the skin in the zone near the application of the load. This first delamination led to a first decrease of the load curve. Increasing the deformation, a further delamination occurred on one side of the specimen leading to a sharp and sudden drop of the applied force. Then, the material showed an almost constant load trend due to the ductile nature of the material.
The load-displacement curve of the shear tests showed an elasto-plastic behaviour. In the central area of the specimen the fibres tended to slip and compact. This led to an increase of the load in the final part of the test. No test resulted in specimen breaking.
A more detailed analysis of the results of the standard tests made on the PURE© was discussed by the authors in [25].

3.2. STANDARD TESTS ON CFRP AND HYBRID SPECIMENS

The tensile tests put in evidence a higher load capacity of the specimens made completely of CFRP (Figure 5A), than the hybrid solution (Figure 6A). Moreover, the full CFRP specimens showed a higher sensitiveness to the thickness variation, because the percentage variation of the stiffness (in terms of average slope of the load-stroke curve), between the different thickness is higher than the percentage variation of the thickness.

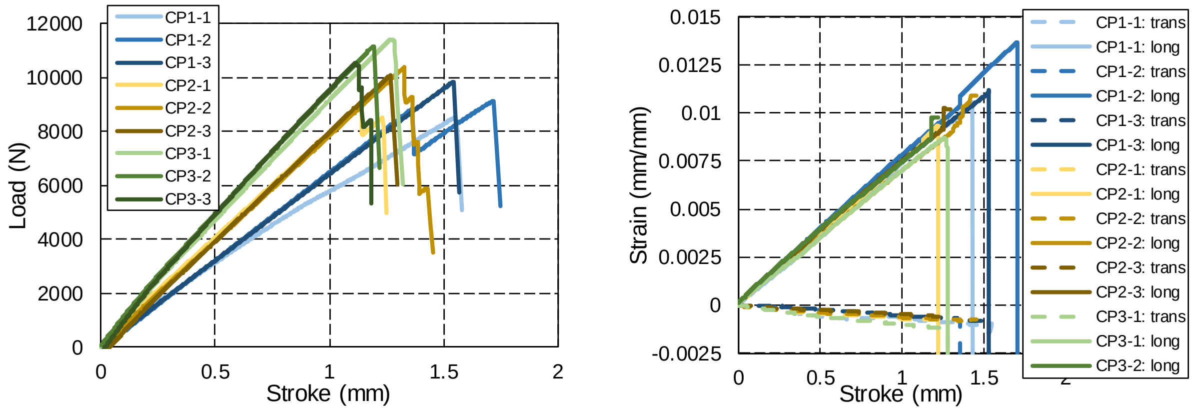
As expected, both materials broke brittle. This was evident from the sudden fall of the load after the first peak.

Some additional load peaks were observed for the hybrid specimens, followed by sharp and sudden load drops. This behaviour described a failure due to a marked delamination between the layers made of different material. This effect was larger in the thicker specimens due to the higher number of stacked layers. The delamination in these specimens was also clearly observable by naked eye after the tests, as shown in Figure 7. The lack of adhesion between the CFRP layers and the PURE© layers was due to the different nature of the stacked materials. The consequent premature delamination was the main reasons of a general lower load capability of the hybrid laminates compared to the all CFRP laminates. Analysing the strain-stroke diagrams for both materials (Figures 5B and 6B) it is worth to observe that the hybrid specimens demonstrated an overall higher strain to failure respect to the CFRP specimens. The plastic nature of the polypropylene and the non-uniform adhesion between the layers with a subsequent delamination can be considered the main causes of this difference. However, in both cases the thicker specimens were subjected to a lower strain at maximum load.



(A) (B)

Figure 5: Load-displacement (A) and strain-displacement (B) curves of CFRP specimens subjected to tensile test. The colours of the curves refer to the thickness of the specimens (Table 1).



(A) (B)

Figure 6: Load-displacement (A) and strain-displacement (B) curves of hybrid specimens subjected to tensile test. The colours of the curves refer to the thickness of the specimens (Table 1).

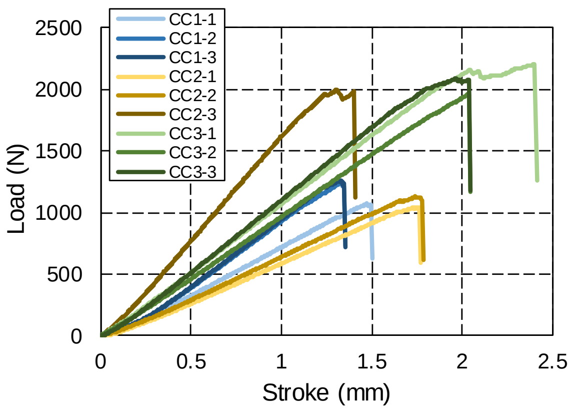
Figure 7: Side view of a CFRP-PURE© specimen after the tensile test.

The Figure 8 shows the layout of the bending tests for two types of specimens. The results of the bending tests, in terms of load-displacement and stress-strain curves, are shown in Figures 9 and 10. As expected, the trend of the curve for the full CFRP specimens is dominated by the elastic behaviour and by a brittle failure. The load capacity dropped to zero after a maximum value of the load. The thicker specimens exhibit further post-peaks load increases due to carbon layer compaction. As regard the stress-strain characteristic (Figure 9B), it is possible to note that all the curves showed the same trend. The stress peaks between different thickness configuration are comparable, except for the specimen CC-1-1. In this last case the specimen supports a higher value of stress-to-failure. This effect was mainly due to a higher level of compaction during polymerization and a lower presence of voids into the specimen. Contrary, the hybrid specimens showed a clear separation between the stress-strain curves (Figure 10B) obtained with the different thickness. The maximum load supported by the hybrid specimens was about one order of magnitude lower than that of the fully CFRP specimens, as shown in Figure 10A. The hybrid specimens showed two different behaviours. The thinner specimens exhibited higher load capacity than the thicker specimens and the behaviour was similar to the full CFRP specimens. However, in this case a slight decrease in the bending stiffness increasing the load applied was also observed. The specimens with the two higher thicknesses showed a behaviour dominated by the PURE material: the global behaviour of the specimens showed a first load peak for a low value of the deformation. After the first peak, the load increases with a very low rate because the specimens were dominated by a plastic behaviour. This behaviour was due to the ductile nature of the PURE© which creates a compaction of the PURE© layers. A slip of the specimen on the lower supports and a reduction of the thickness of the specimens were also observed. The detachment between the layers made of CFRP and the layers made of PURE©, due to different chemical composition of the two materials was also observed in these type of tests (partially visible in Figure 8B.

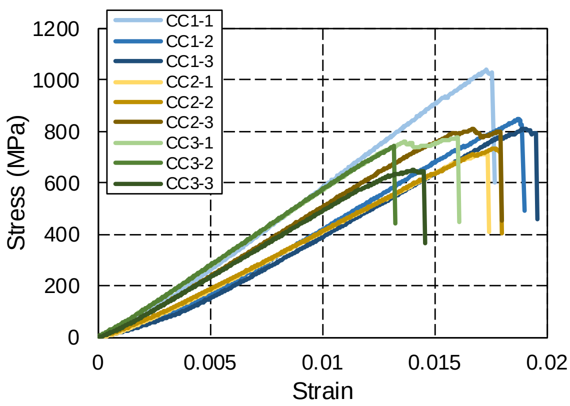
(A)

(B)

Figure 8: Bending test layout: fully CFRP specimen (A) and hybrid configuration (B).

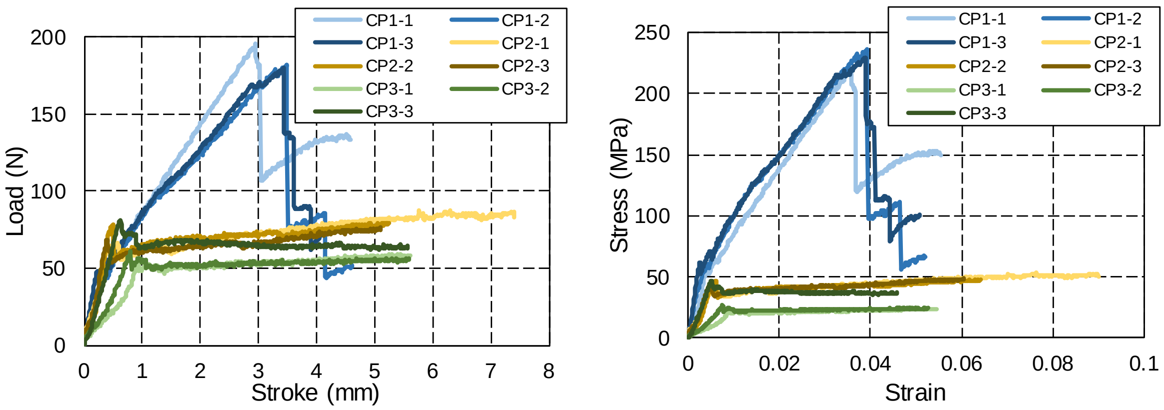


(A)



(B)

Figure 9: Load-displacement (A) and stress-strain (B) characteristic of the CFRP specimens subjected to bending test. The colours of the curves refer to the thickness of the specimens (Table 1).



(A) (B)

Figure 10: Load-displacement (A) and stress-strain (B) characteristic of the hybrid specimens subjected to bending tests. The colours of the curves refer to the thickness of the specimens (Table 1).

3.3. CRUSH TESTS ON IMPACT ATTENUATORS

Quasi-static and dynamic impact test were performed on the impact attenuator completely made of CFRP. In both cases, a brittle crushing behaviour was observed (Figure 11) with formation of splinters and debris. After the test, the fibre layers were bent both internally and externally. The two-sudden wall thickness variation along the axial direction caused two load peaks as it is possible to understand from the chart shown in Figure 12. These results highlighted as the discontinuities in the ply thickness should be reduced, or even a continuous thickness variation should be preferable to avoid sharp load peaks [18].

Figure 11: Full CFRP impact attenuator after the dynamic crush test.

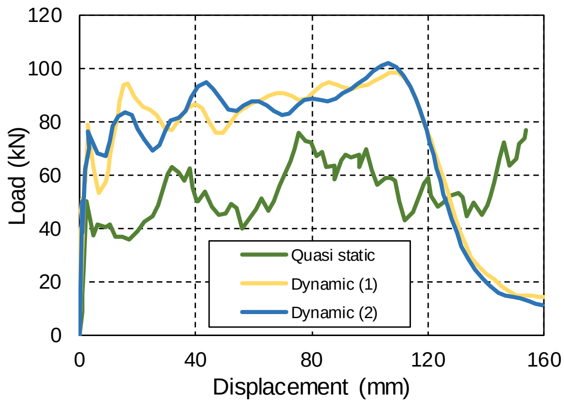


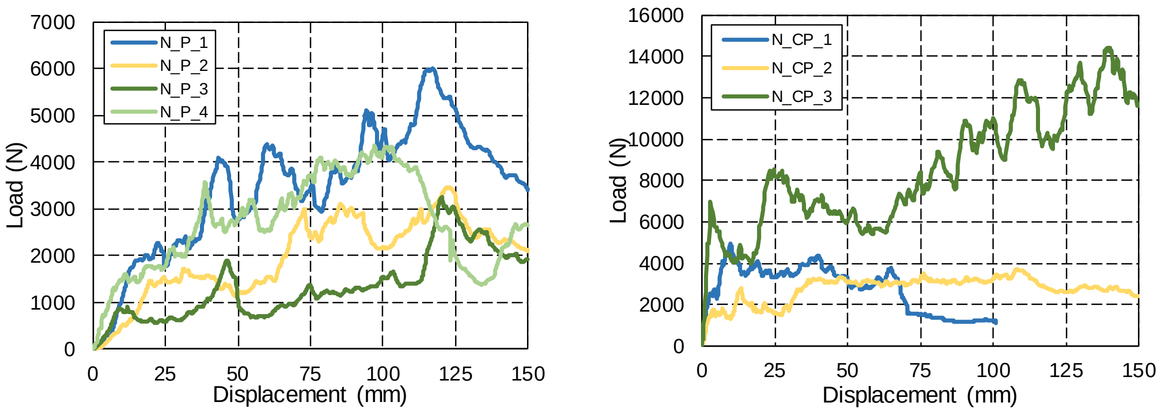
Figure 12: Force-displacement curve of the fully CFRP impact attenuators subjected to crush tests.

The curves of crush load-displacement for the attenuator completely made of PURE© (Figure 13A) are shown in Figure 14A. The fully PURE© attenuators showed a ductile and plastic behaviour during the crush. The layer folding was the main failure mode as it is possible to see in Figure 15. Similarly, to what was observed for the CFRP specimens, the thickness discontinuities led to force peaks. The maximum load is about of one order of magnitude lower than that observed for the full CFRP components. The load-displacement curves continuously increased with the material folds, even if in a more irregular and scattered way compared to the fully CFRP specimen. This behaviour was justified by the layer compaction. In Figure 14B it is possible to distinguish three trends for the hybrid components according to the different stacking sequence of the specimens. Despite the presence of the carbon fibre, the load and the absorbed energy of the components N_CP_1 and N_CP_2 is quite comparable to the full PURE© attenuators. This result is due to the production process. A good grade of adhesion between carbon and PURE© layers cannot be reached since the thermoset and the thermoplastic composites require different curing process. The pressure and the temperature range used in the production process are dissimilar for the two materials. The cure of the epoxy resin requires high temperature, not suitable for the thermoplastic materials. When the PURE© was subjected to those temperatures an uncontrollable shrinkage occurred. Furthermore, the pressures must be much higher than 10 bar to avoid the shrinkage. According to that, a partial lack of ply adhesion at the end of the production process led the carbon and the PURE© layers to an ease delamination during the crushing. The failure mode of the N_CP_1 and the N_CP_2 attenuators can be observed in Figure 16. The highest capability of energy absorption was found for the N_CP_3 configuration, where the lamination process had additional steps. The load-displacement curve of the N_CP_3 (Figure 14B) shows a progressive increase of the force with the crushing. This behaviour was different from that obtained with the CFRP specimens, where the increase of the load had a slower slope. This can be due to the dimension of the hybrid cross section that tended to increase faster than that of the PURE© one during the crushing. This behaviour was caused by the detachment of the external carbon layers from the internal core made of polypropylene.

Considering the energy absorbed during the crushing and reported in Figure 17, a higher energy absorption capability of the N_CP_3 specimen was also observed. As conclusion, the curing of the thermoplastic material before the compaction of the lamina with the thermosetting material, seems to be an interesting solution from the manufacturing process point of view. This solution can be adopted when a hybrid configuration is considered in order to take the advantages of two materials. However, it should be pointed out that the absorbed energy for the hybrid configuration is an order of magnitude lower than that obtained with the attenuator made of fully CFRP (where 7 kJ were absorbed for a total crushing of about 110 mm) and therefore further research on such topic is worthy of investigation.

(A) (B)

Figure 13: Fully PURE© (A) and hybrid (B) impact attenuators.



(A) (B)

Figure 14: Force-displacement curves of fully PURE© (A) and hybrid components (B) obtained during the quasi-static crush tests.

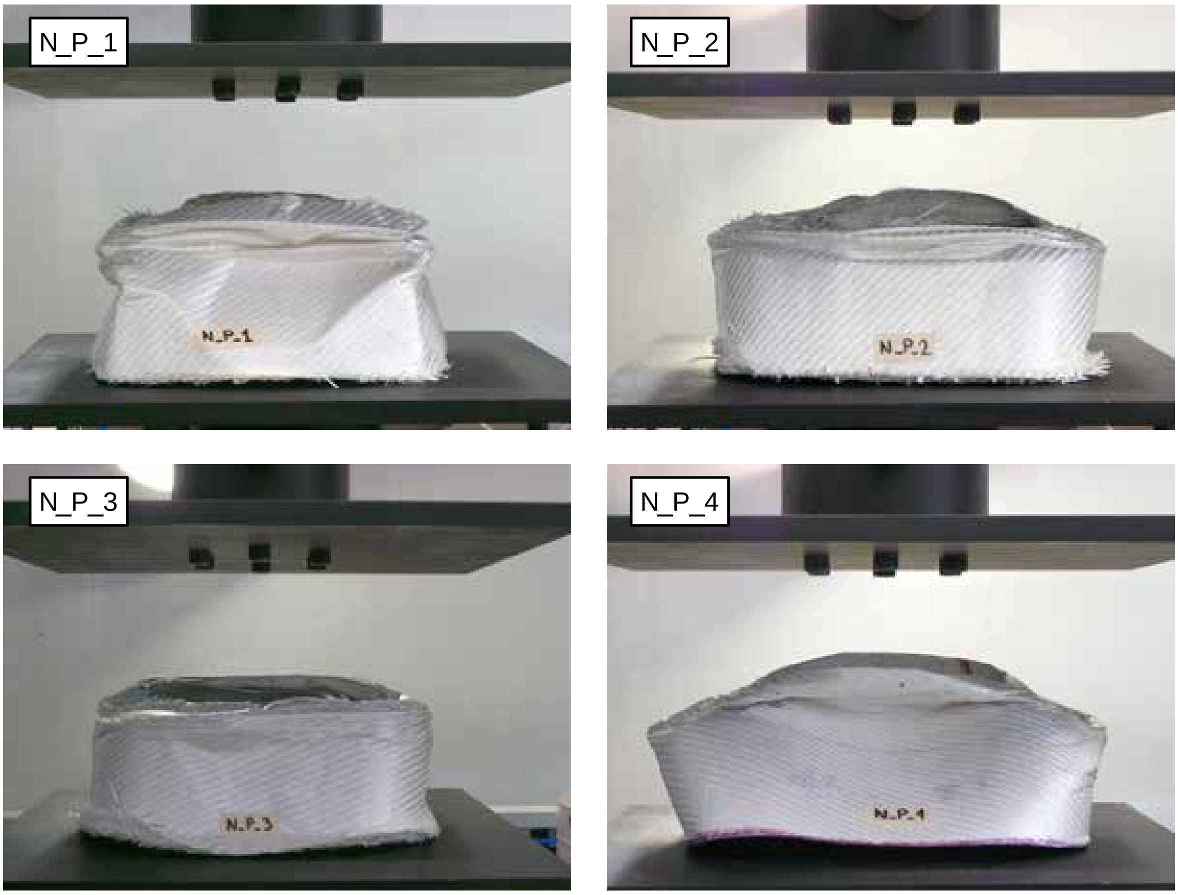


Figure 15: Full PURE© impact attenuators before (left hand side) and after (right hand side) the crush test.

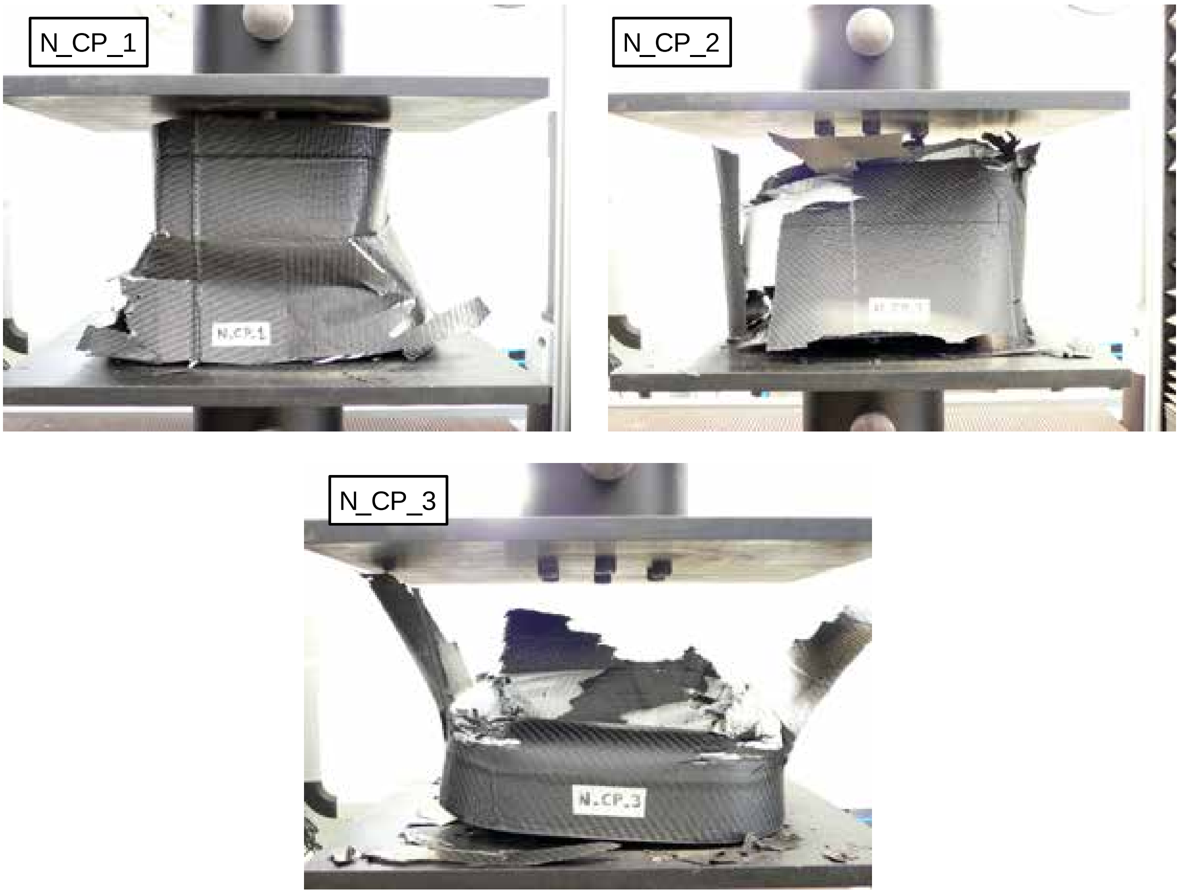
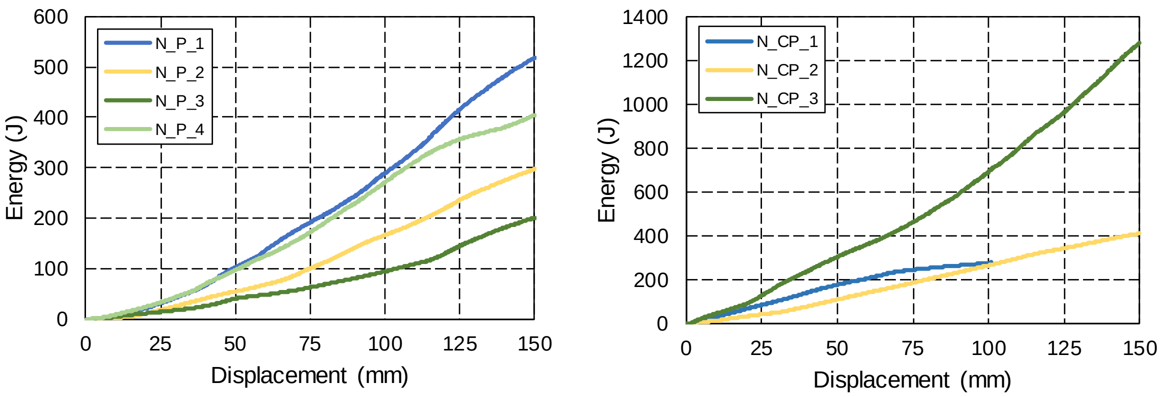


Figure 16: Hybrid impact attenuators before (left hand side) and after (right hand side) the crush test.



(A) (B)

Figure 17: Energy absorption of full PURE© (A) and hybrid components (B).

4. CONCLUSIONS

In the recent years, the thermoplastic composites are of great interest in the automotive field for their mechanical properties, lightweight and recyclability. In this work, the mechanical behaviour of composite material made up of fibre and matrix polypropylene (PURE©) was investigated. This material is intended for the production of structural components as it is or in combination with thermoset laminates obtaining innovative hybrid composite. Accordingly, experimental standard tests were executed on standard specimens to define the material properties of three class of materials: fully CFRP, fully PURE© and hybrid CFRP-PURE©. Moreover, crushing tests in quasi-static conditions were carried out on impact attenuators considering the three composite materials. These components can be used as front member for the racing car of Formula SAE. Considering the crushing tests, the thermosetting specimens showed a plastic and ductile response with the delamination as the main failure mode. The ductile response is due to the plastic nature of the material. The test executed on the fully PURE© attenuators showed a good energy absorption capability. A plastic behaviour was noticed, and the regular folding was the main failure mode. The presence of three peaks in the load-displacement curves suggested that sudden change in the wall thickness should be avoided. However, the increase of the thickness along the longitudinal axis of the attenuator is important to get a progressive energy absorption with the crushing. The hybrid attenuators were made using three different stacking sequences alternating layer of CFRP and of PURE©. Two solutions showed an energy absorption capability comparable to those obtained with the fully PURE© attenuators. These results were due to a poor adhesion state between the layers of the two materials. This lack of adhesion was caused by the different chemical properties of the thermoplastic and the thermosetting composite material. Consequently, different requirements in terms of pressure and temperature are necessary during the curing process. The delamination occurred easily. The mechanical properties of the component were consequently degraded and the lamina of the specimens showed a marked delamination. A sandwich configuration between the two materials was also investigated. In this last solution two carbon skins covered a core made completely of PURE©. Moreover, the PURE© layers were precured. In order to obtain a better compaction in the lamina, the voids created by the withdrawal of the PURE© were compensated by carbon layers. This solution showed the better results in terms of maximum force and energy absorption obtaining a progressive increasing of the force-displacement curves. The maximum peaks of the load were about twice the peaks obtained with the fully PURE© solutions. The performance of the hybrid solution was also compared with that obtained by a similar fully CFRP attenuator. It was observed how the absorbed energies of the hybrid attenuators affected by delamination were not comparable with the fully CFRP solution. The results of the work highlighted the need to precure the layers of PURE© laminas when they are used to produce hybrid laminates. Furthermore, in order to get the best results in terms of energy absorption, the adhesion between the layers of the thermoset and thermoplastic materials during the production of hybrid laminates had to be carefully investigated.

REFERENCES

[1] S. Hoffenson, Safety considerations in optimal automotive vehicle design, PhD Dissertation, University of Michigan, 2012

[2] G. Belingardi, G. Chiandussi, E. Gobetto, A. Scattina, Bonnet weight reduction and VRU protection: Design proposals implementing non-conventional materials, International Journal of Automotive Technology, 11(6), 2010, 831-842.

[3] M. Avalle, G. Belingardi, A. Scattina, Numerical and experimental investigation of a lightweight bonnet for pedestrian safety, International Journal of Crashworthiness, 18(1), 2013, 29-39.

[4] F. Mo, P.J. Arnoux, M. Avalle, A. Scattina, E. Semino, C. Masson, Incidences of various passenger vehicle front-end designs on pedestrian lower limb injuries, International Journal of Crashworthiness, 20(4), 2015, 337-347.

[5] Proposal for a regulation of the European parliament and of the council: setting emission performance standards for new passenger cars and for new light commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from light-duty vehicles and amending Regulation (EC) No 715/2007. (26 January 2018).

[6] Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. Official Journal of the European Communities (21 October 2000).

[7] J.D. Muzzy, A.O. Kays, Thermoplastic vs. thermosetting structural composites, Polymer Composites, 5 (3), 1984, 169-172.

[8] R.Vodicka, Thermoplastics for Airframe Applications A Review of the Properties and Repair Methods for Thermoplastic Composites, DSTO Aeronautical and Maritime Research Laboratory, Melbourne, October 1996.

[9] F.C.Campbell, Thermoplastic Composites: An Unfulfilled Promise, Manufacturing Processes for Advanced Composites, 357-397, 2004.

[10] Adel Zaki El-Sonbati, THERMOPLASTIC – COMPOSITE MATERIALS, Published by InTech, Croatia, 2012.

[11] P.Wang, N.Hamila, P.Boisse, P.Chaudet, D.Lesueur, Thermo-mechanical behavior of stretch-broken carbon fiber and thermoplastic resin composites during manufacturing, Polymer Composites, 36 (4), 694-703, 2015.

[12] C.Vacogne, R.Wise, Joining of high performance carbon fibre/PEEK composites, Science and Technology of Welding and Joining, 16 (4), 369-376, 2011.

[13] I.Noll, R.Brull, N.Vestweber, G.Seide, T.Gries, Application of polyetherimide in automotive body parts with Class-A surface and thermal stress, Fiber Society 2015 Fall Meeting and Technical Conference-Fibers:Where Tradition Meets Innovation, North Carolina State University Raleigh, United States, 28-30 October 2015.

[14] J.Starke, Carbon composites in automotive structural applications, BMW Group, EuCIA:Composites and Sustainability, 19 March 2016, Brussels

[15] Y.Yagi, Changing the Future of Carbon Fiber Reinforced Thermoplastic Composites, Teijin Advanced Composites America, http://www.temp.speautomotive.com/SPEA_CD/SPEA2016/pdf/CF/CF4.pdf

[16] N.Cabrera, B.Alcock, J.Loos, T.Peijs, Processing of all-polypropylene composites for ultimate recyclability, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 218(2), 2004,145-155.

[17] J.Obradovic, S.Boria, G.Belingardi, Lightweight design and crash analysis of composite frontal impact energy absorbing structures, Composite Structures, 94 (2), 2012, 423-430.

[18] S.Boria, J.Obradovic, G.Belingardi, Experimental and numerical investigations of the impact behavior of composite frontal crash structures, Composites: Part B, 79, 2015, 20-27.

[19] S.Boria, A.Scattina, G.Belingardi, Axial energy absorption of CFRP truncated cones, Composite Structures 130, 2015, 18-28.

[20] B.Alcock, Single polymer composites based on polypropylene: processing and properties. UK: Queen Mary, University of London; 2004.

[21] S.Boria, A.Scattina, Energy absorption capability of laminated plates made of fully thermoplastic composite, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 232(8), 2018, 1389-1401.
[22] S.Boria, A.Scattina, G.Belingardi, Impact behavior of a fully thermoplastic composite, Composite Structures 167, 2017, 63-75.
[23] Formula SAE rules; 2008, http://students.sae.org/competitions/formulaseries/rules/rules.pdf .
[24] R.Van Moorleghem, Welding of thermoplastic to thermoset composites through a thermoplastic interlayer, Msc. Thesis, Technische Universiteit Delft, 2016.
[25] S.Boria, A.Scattina, G.Belingardi, Experimental evaluation of a fully recyclable thermoplastic composite, Composite Structures, 140, 2016, 21-35.

List of figures

List of Tables