# IMPACT BEHAVIOUR OF A FULLY THERMOPLASTIC COMPOSITE

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## ABSTRACT

Composites are materials of choice for lightweight structures due to their excellent strength/weight/ and stiffness/weight/ properties. For several years, the application of composite materials with continuous fiber was limited to those with thermosetting matrix. Recently, interest in composites with thermoplastic matrix is growing thanks to their considerable advantages also in terms of recyclability. The thermoplastic composites appear to be the right alternative to the materials currently used, replacing not only the non-structural parts, but also the structural components located in areas potentially subject to impacts.

This paper presents the results of an experimental campaign made on a fully thermoplastic composite, where both the reinforcement and the matrix are made in polypropylene. The target is to analyze its behavior under different impact loading conditions using a drop weight testing machine. The influence of the impact mass and of the velocity on the energy absorption capability of the material have been analyzed and discussed. During the tests, the material showed a ductile behavior and developed extended plasticity without a crack tip. The main observed damage mechanisms were the yarn sliding.

## 1 INTRODUCTION

Composites are materials used for lightweight structures due to their excellent weight/strength and weight/stiffness properties [1-3]. Composite materials are often used for impact applications [4]. The behavior of composite structures subjected to low velocity impact has received considerable attention in the recent literature [5-13]. Low velocity impact (defined as events in the range 1–10 m/s) can cause matrix cracking, delamination and fiber breakage. Experimental studies put in evidence as, during the low-velocity impacts, the damage initiates with matrix cracks. These cracks cause delamination at the interfaces between plies that have different fiber orientations than each other. For thin specimens, the bending stresses, due to the impact, cause matrix cracking in the lowest ply, and the damage propagates from the bottom through the other plies up to the impacted face. The damage is characterized by the matrix cracks and the delamination in the ply interfaces, like a reversed pine tree [14]. For stiffer specimens, the matrix cracks initiate on the impacted surface of the specimen due to the high contact stresses. The damage propagates from the top surface to the bottom one through the other plies like a pine tree [15]. Such damages are very difficult to be detected with the naked eye and can lead to severe reductions in the stiffness and the strength of the structures. Consequently, the study of the behavior of the composite structures subjected to low velocity impact is essential to avoid loss of performance.

In the past years, many researchers focused their interests on the impact behaviors, on the damage mechanisms and on the residual strengths of the composite structures. These studies are well summarized by Abrate [8, 16] and Richardson [9]. Several researchers have devoted their investigations to model the damage development in the composite structures [17-19]. The low velocity impact behavior of the composite materials has been studied, from an experimental point of view, by several authors [10-12]. Between the others experimental methodologies, the drop weight impact tests have been used for this type of research. Other authors have proposed analytical formulations for the prediction of the impact behavior on composite laminates [8, 16, 21]. However, due to the complexities of the impact behavior and of the impact damage, the analytical methods often result in an oversimplification of the problem. Moreover, the solutions proposed are only applicable to simplified models. Furthermore, experimental approaches are both time consuming and expensive. Therefore, an efficient numerical analysis tool [20] is usually adopted to investigate this phenomenon. A number of studies have been performed to analyze, from a numerical point of view, the behavior of the composite plates over the last few years [11, 12, 19, 22-24]. These studies mainly focused on the development of numerical methods to understand the impact behavior of the composite plates under low velocity impacts.

Moreover, in order to assess their capability to withstand load, the growing use of the polymeric materials in engineering applications demands new methodologies, such as the bulk resin modification and the interlaminar toughening. Nash *et al.* [25] have presented a review of the state-of-art about the incorporation of a thermoplastic phase into a fibre-reinforced thermosetting composite laminate in order to improve its damage resistance and tolerance properties, when subjected to a low-energy impact. It is well known that thermoplastics, even the toughened grades, are relatively susceptible to impact fracture [26]. Therefore, the impact testing is widely used to characterize the fracture resistance of the polymers in industry, because it attempts to simulate the most severe loading conditions to which a material can be subjected in the working environments. Furthermore, this type of test diminishes the effects of the matrix viscoelastic behavior, so that it becomes sufficiently reasonable to neglect them. However, the difficulty to obtain reliable data from the instrumented impact tests at various speeds is well known and pointed out in the literature [27-29].

In this perspective, the target of this work is to analyze the behavior of a fully thermoplastic composite under different impact loading conditions. Both the reinforcement and the matrix of the considered composite are made in polypropylene. The study has been carried out with a series of experimental drop dart tests. The influence of different parameters, like the velocity and the mass of the impact, on the structural behavior and on the energy absorption has been evaluated.

## 2 PRODUCING LAMINATED COMPOSITES FOR EXPERIMENT

The material studied in this work is a sealable, co-extruded triple layer polypropylene (PP) tape. It was provided by Lankhorst Pure Composites and produced via the patented PURE technology [30]. The PURE tapes were used for weaving into thermoformable plain fabric processes. A mono material concept, which is fully recyclable, has been achieved using PP fibers embedded in the same PP matrix. In Table 1, the main mechanical properties of the tape and the sheet configuration are reported according to the PURE technical data sheet.

| PURE tape | Test method | Value | Unit |
|---|---|---|---|
| E-modulus | ISO 527 | 14 | GPa |
| Tensile strength | ISO 527 | 500 | MPa |
| Elongation | ISO 527 | 6 | % |
| Shrinkage at 130° | ASTM D4974 | <5.5 | % |
| Sealing range | | 130-180 | °C |

| PURE sheet | Test method | Value | Unit |
|---|---|---|---|
| Bulk density | ASTM D792 | 0.78 | $g/cm^3$ |
| Tensile modulus | ISO 527-4 | 5.5 | GPa |
| Tensile strength | ISO 527-4 | 200 | MPa |
| Tensile strain to failure | ISO 527-4 | 9 | % |
| Flexural modulus | ISO 178 | 4.5-5.5 | GPa |
| Charpy impact (FN) | ISO 179 | (N, no break) | $kJ/m^2$ |
| Charpy impact (EP notched type A) | ISO 179 | (P) 140 | $kJ/m^2$ |
| Izod impact (FN) | ISO 180 | (N, no break) | $kJ/m^2$ |
| Izod impact (EP notched type A) | ISO 180 | (P) 126 | $kJ/m^2$ |
| Instrumented falling dart impact (23°C) (2.2 mm, clamped, 20 mm striker) | ISO 6603-2 | 9.51<br>51.46 | kN (peak)<br>J (at failure) |
| Heat deflection temperature (1820 kPa) | ASTM D648 | 95 | °C |
| Coefficient of thermal expansion (-20°C to 100°C) | ASTM E228 | 23 | $10^{-6}$ $K^{-1}$ |
| Coefficient of thermal conductivity (2.25mm) | EN-ISO 12567-1 | 0.044 | W/m K |
| Fire behaviour-burning rate (1.6mm) | ISO 3795 | 29 | mm/min |

**Table 1:** Mechanical properties for the PURE tape and sheet.

In our case, the PURE fabrics were consolidated into a 600x1200 mm sheet using 53 layers of material. The laminate was put into a hot press. The compaction process was carried out at the pressure of 100 bar and at the temperature of 130°C for 2 hours. After this process, the laminate was cut into specimens with square shape, with an edge length of 100 mm, using the waterjet technology. A specimen example is shown in Figure 1. The final thickness of the composite specimens was about 6.9 mm.

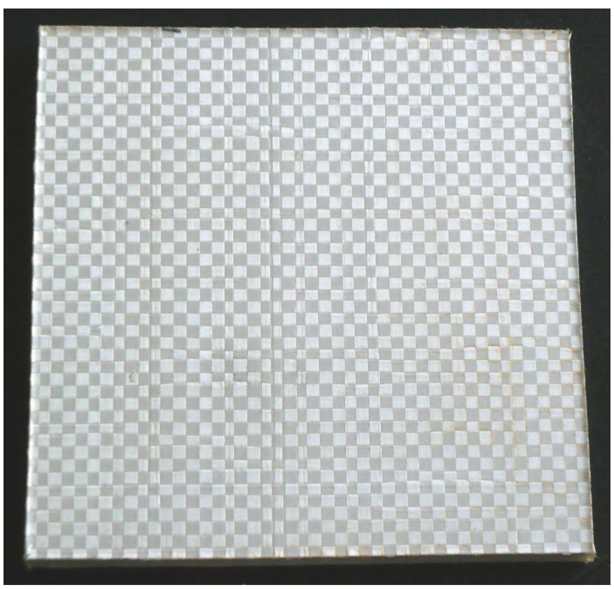


**Figure 1:** PURE specimen before the test.

## 3 DROP WEIGHT IMPACT TESTING

To study the impact behavior of the thermoplastic composite object of this work, drop weight impact tests were carried out on the described specimens . The drop weight impact testing is a type of low velocity testing, and it is the most common test used to analyze the impact behavior of composite plates [31-35]. In this type of test, a defined mass is raised to a known height and released (Figure 2 on the left). The mass is driven in its free fall with a couple of rails. A dart impactor with a hemispherical tip, fixed to the mass, strikes the specimen. The diameter of the dart and of its tip was 20 mm. The testing device used for these tests was the Ceast 9350 (Figure 2, on the right). The main parameters of the tests were the mass of the impactor *W* and the impact velocity $v_0$. This last parameter was measured with a photocell whereas the mass of the impactor can be changed applying metal plates on the impactor structure. The metal plates have a calibrated weight. The testing machine has a maximum fall stroke of 1 m and is equipped with a system of springs when higher impact energy is requested, up to a total equivalent fall height of 29 m. The load applied by the impactor, when it is in contact with the specimen, is measured with a piezoelectric load cell. This device is fixed behind the hemispherical tip. The data acquisition system had a sampling frequency of 1 MHz and no filters were applied on the force signal. During the tests, the flat specimens were clamped into the testing machine. The clamping device has a central circular hole with an internal diameter of 76 mm. Consequently, the specimens has a circular free surface with a diameter of 76 mm. The orientation of the weft of the specimen material does not affect the results of the tests due to the shape of the clamping device.

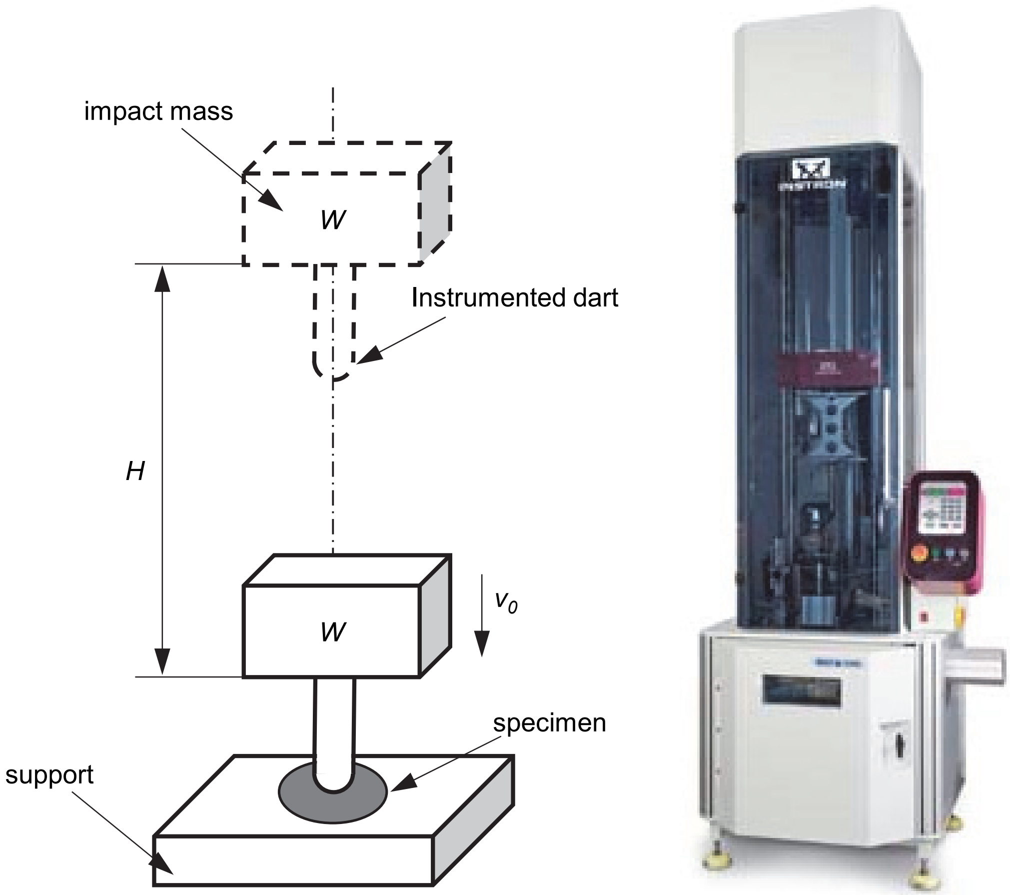



**Figure 2:** Pattern of the drop weight test (on the left), the testing machine used for the experimental tests (on the right).

The dynamic behavior of the full thermoplastic composite has been studied evaluating the effect of the mass of the impactor *W* and of the impact velocity $v_0$. To this aim, the experimental tests have been carried out considering two different levels for the mass *W* and three different levels for the impact velocity $v_0$. For the mass of the impactor *W*, the lower level adopted has been the minimum value available on the testing machine, whereas the upper level has been obtained applying all the available additional masses. For what concerns the values of the impact velocity $v_0$, they have been defined in order to obtain the, as precisely as possible, same three levels of kinetic energy for the two considered masses. The three values of energy have been equally spaced. The considered experimental test configurations are summarized in Table 2. A slight difference in the energy levels for the two values of mass were obtained. However, these differences are quite small and so that can be considered of negligible affection on the results. Consequently, in the following discussions, we have decided to make reference to the same three levels of energy for the two masses. The reference values of the energy levels are shown in Table 2.A full factorial plane has been considered, for a total amount of six different configurations.. For each test configuration, three different repetitions have been performed.

| # | Mass of the impactor *W* (kg) | Impact velocity $v_0$ (m/s) | Energy level |
|---|---|---|---|
| 1 | 7.3 | 3.8 | 1 (~57 J) |
| 2 | 7.3 | 6.2 | 2 (~144 J) |
| 3 | 7.3 | 9.6 | 3 (~342 J) |
| 4 | 67.3 | 1.3 | 1 (~57 J) |
| 5 | 67.3 | 2.1 | 2 (~144 J) |
| 6 | 67.3 | 3.2 | 3 (~342 J) |

**Table 2:** Experimental test configurations considered in the work.

# 4 EXPERIMENTAL RESULTS

The contact force as a function of the time history was recorded during the contact between the impactor and the specimen. The velocity history and then the displacement history can be calculated dividing the force history by the mass of the impactor and then integrating with respect of the time using the initial impact velocity $v_0$. The kinetic energy of the impactor just before the contact with the specimen is the impact energy *E*, that is the energy transferred to the composite specimen. A portion, or the total amount, of the impact energy can be absorbed by the composite specimen in forms of material damage, heat generation and other mechanisms [36]. Therefore, for each experimental test, the force-displacement and the absorbed energy history were evaluated. In this type of tests, two categories of damage can occur. The first is an impact damage, clearly visible with the naked eye. The second type of damage is a barely visible impact damage, which can seldom be seen with the naked eye. Some damages are in fact categorized as internal defects and generally consist of matrix cracking and fiber breakage which usually cannot be detected by simply examining the surface of the specimen [37]. The evaluation of the both types of damage can be enhanced using post-impact inspection, such as ultrasound, microwave, x-ray, optical, scanning electron microscopy (SEM), and thermographic testing [38]. Some specimens show the failure modes only at the contact area of the impactor. For low velocity impacts, damage starts to propagate with the formation of a matrix crack [39-40]. Delaminations, which form the critical failure mode after impact damage, propagate due to high transverse shear stresses nearby the impacted surface [41-42]. The initiation and growth of delamination will results in progressive stiffness degradation. The damage will later propagate into other failure modes with the introduction of significant fibre damage and further developing into fibre fracture and fibre pullout [43-44].

As well known, in a FRP composite structure, the impact behaviour due to drop weight impact testing can occur in three ways: rebounding, penetration and perforation [45-46]. However, in the experiments carried out in this work, only the first two types of impact damage occurred, whereas no perforation was observed due the high thickness of the specimens. The contact force, the deflection, the impact velocity and the impact energy as a function of the time are plotted in Figures 3 and 4 to explain the different damage types.

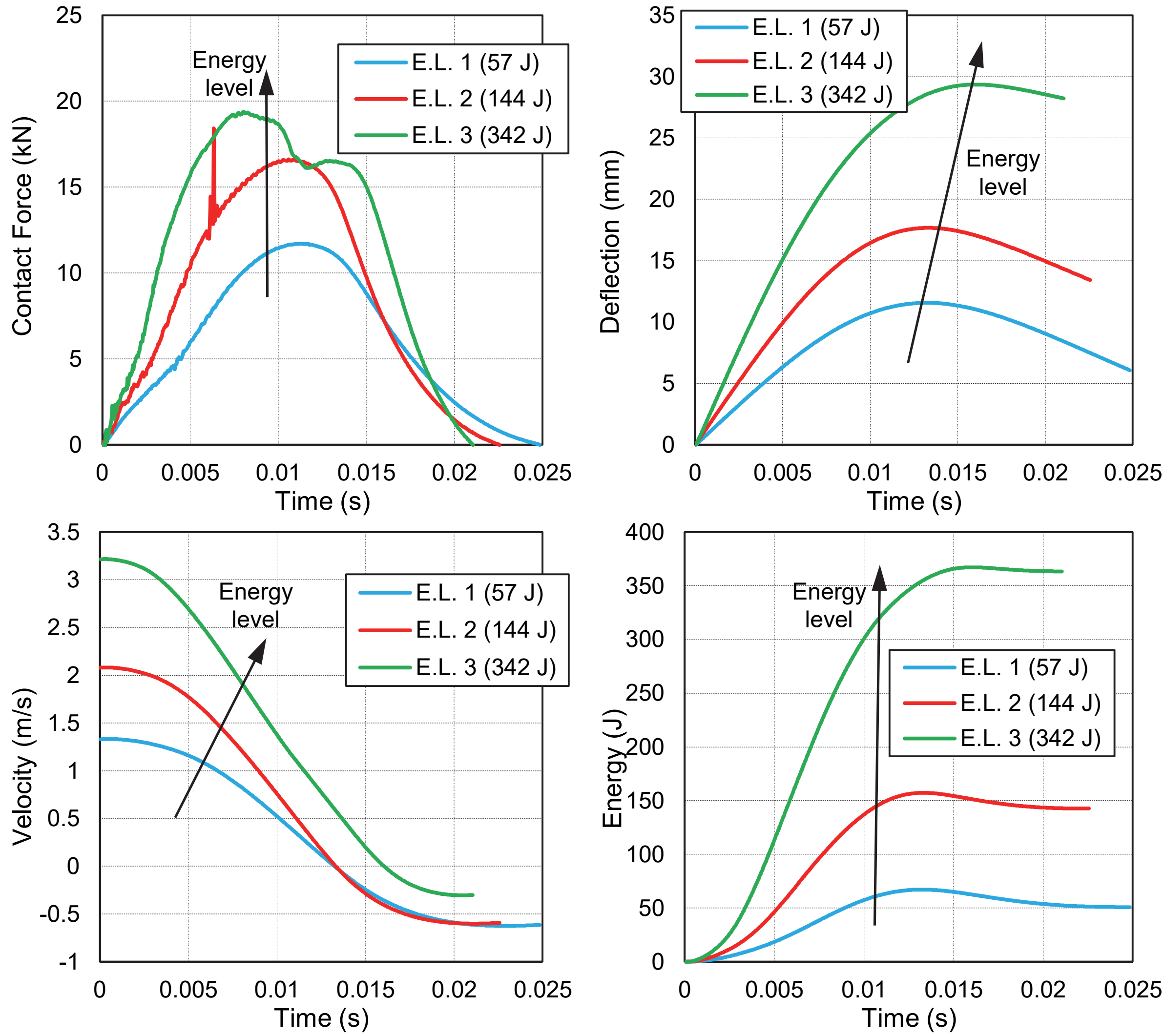



**Figure 3:** Example of the four main parameters evaluated in the experimental tests with an impact mass of 67.3 kg.

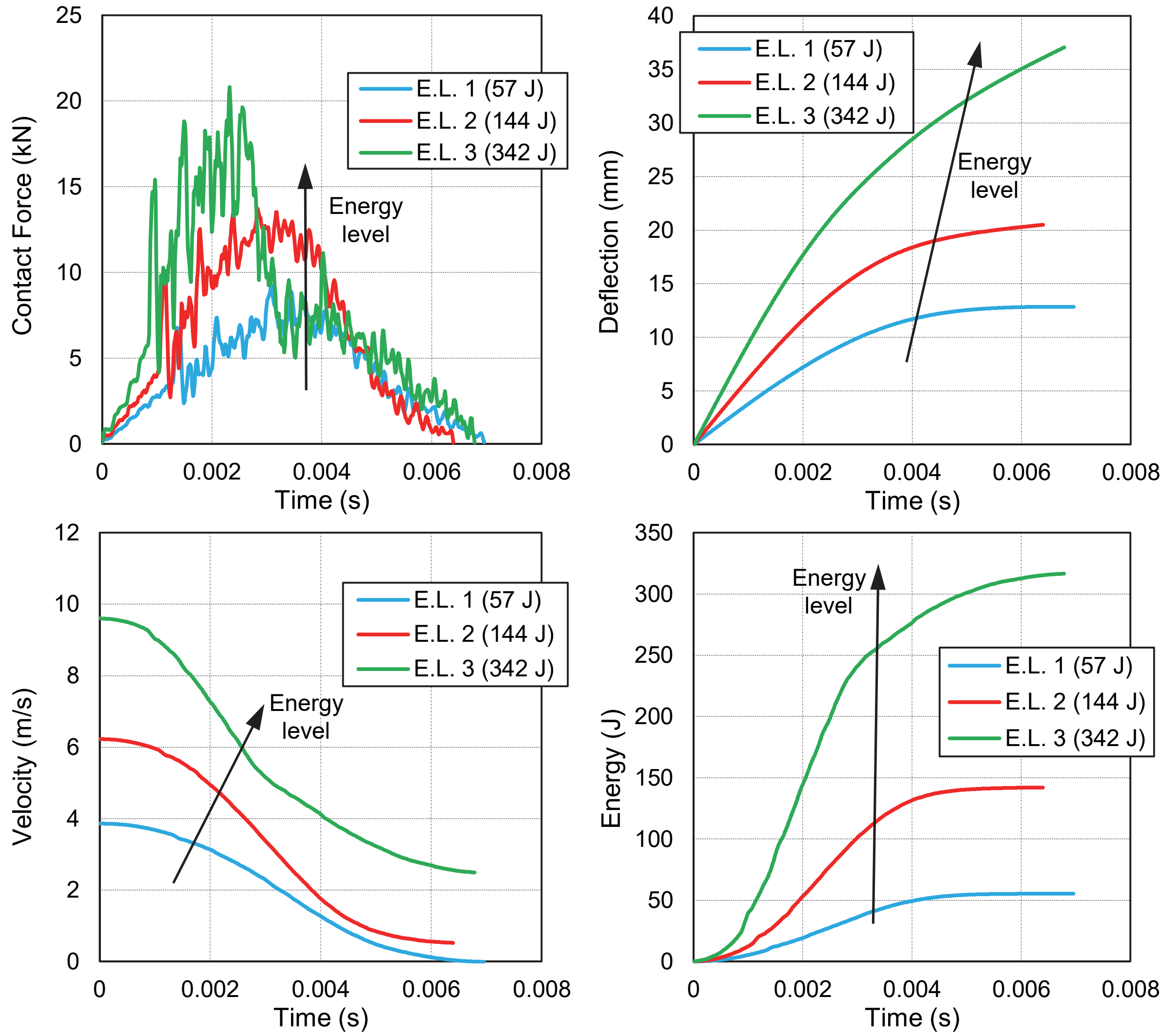



**Figure 4:** Example of the four main parameters evaluated in the experimental tests with an impact mass of 7.3 kg.

The charts in the Figures 3 and 4 show the results obtained with the three different energy levels, considering the same impact mass for each of the two figures. The curves show as increasing the energy level, the damage process goes from rebounding (that is detectable by the change of sign of the velocity) to penetration, whereas no perforation can be observed. In the experimental tests carried out, unlike common FRP composites, no load drops upon fracture initiation can be observed. The contact force increases to a critical value, and then decreases to a minimum value. Generally, the contact force never becomes zero due to the friction forces between the perforated area (hole) and the impactor, in case of perforation. In this work, no perforation has been detected in the experimental tests as confirmed both by an naked eye observation and by the load-displacement curves of the tests. By examination of the specimen deflection curves it is possible to observe two situations. The displacement of the impactor decreases after reaching a maximum value in the rebounding condition (Figure 3). The deflection increases and then stops at a maximum value in the penetration case (Figure 4). This value is the distance from the impacted surface of the specimen where the impactor nose embedded. Examining the impactor velocity diagram, it is possible to see that the velocity takes a negative value in the rebounding situation (Figure 3). The final velocity becomes zero when the projectile is embedded into the specimen for a fully penetrated impactor. The impact energy level has the greatest effect on the damage process. Decreasing the impactor mass and consequently considering higher velocity, there is a small increase of the penetration in almost all the considered conditions of impact energy. This shows that the velocity is the second most effective parameter in the damage process after the impact energy. Indeed, as discussed in [47], an increase of the impact velocity, as we have passing from the tests made with the heavier mass to those made with the lighter mass, causes a decrease in the stiffness of the material (see also data in table 3). Moreover, from the analysis of the charts in Figures 3 and 4, it is clear that the rebounding occurs when the energy at the instant of the impact is greater than the energy absorbed by the specimen.

The impact energy and the absorbed energy are two important parameters to assess the impact response and the resistance of composite structures. The impact energy is defined as the total amount of the energy introduced to the specimen, whereas the absorbed energy is the energy absorbed by the specimen during the impact event. The diagram, which shows the relationship between the impact and the absorbed energy, is known as ‘‘energy profile”. It is possible to define the damage process of the laminates by comparing the corresponding load–deflection curves, the energy profile diagram and the images of the damaged specimens. With this method, which is called energy profiling method (EPM), it becomes possible to define some impact properties such as the pure elastic limit, the penetration and the perforation thresholds [32, 45]. The Figure 5 shows the three cases of damage types using the EPM: the AB region represents the rebounding case, the BC one represents the penetration case, and the CD represents the perforation case. *Pn* and *Pr* represent the penetration and the perforation thresholds, respectively.

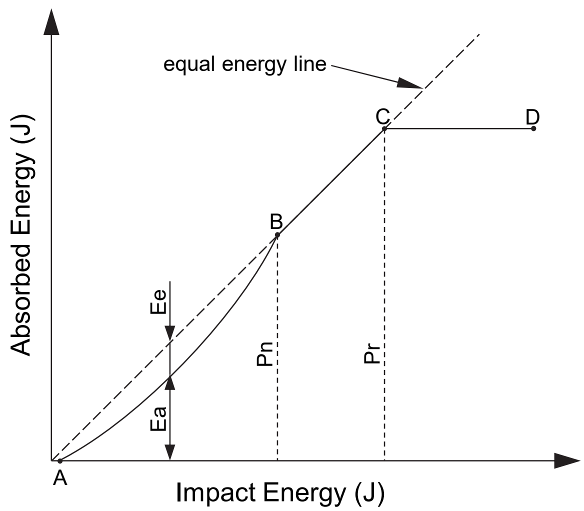



**Figure 5:** The three cases of damage types in EPM [45].

The energy profiling diagram for the PURE specimens is shown in Figure 6. Both the rebounding and the penetration behavior can be observed. Some tests were affected by a slip phenomenon between the specimen and the clamping device during the impact. Moreover, during the production process, in particular in the lamination phase, some strain energy may be absorbed and stored as residual potential energy inside the material. This residual energy may be released during the damage process, by the indentation and the delamination of the material. The presence of residual stresses inside the material was already observed by the authors in [30] studying the tensile behavior of this material.

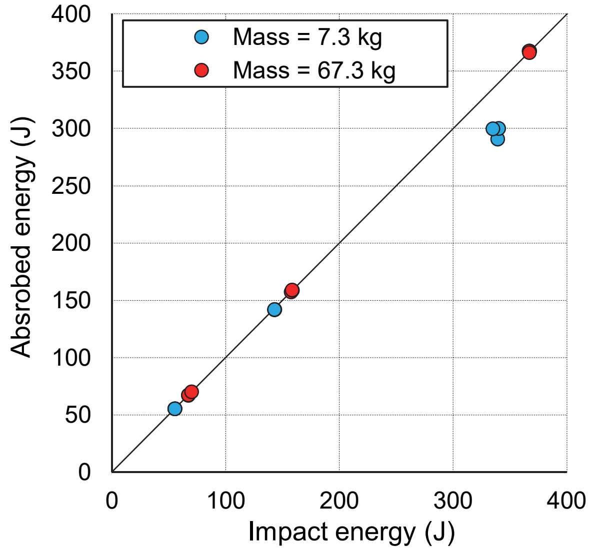


**Figure 6:** Energy profiling diagram for the experimental tests carried out.

The load-displacement curves obtained in the experimental tests are summarized in Figure 7. The curves obtained with the lower mass showed superimposed oscillations of the force signal due to the well-known dynamic effects in the impact testing [29]. Moreover, these oscillations could be due to the vibration of the testing frame with a consequent vibration of the measurement device.

The results show that the mass is the most effective parameter on the damage process together with the impact energy. Generally, for a constant energy level, in the light and fast impacts the penetration behavior was observed whereas in the heavy and slow impacts a rebound behavior was noticed.

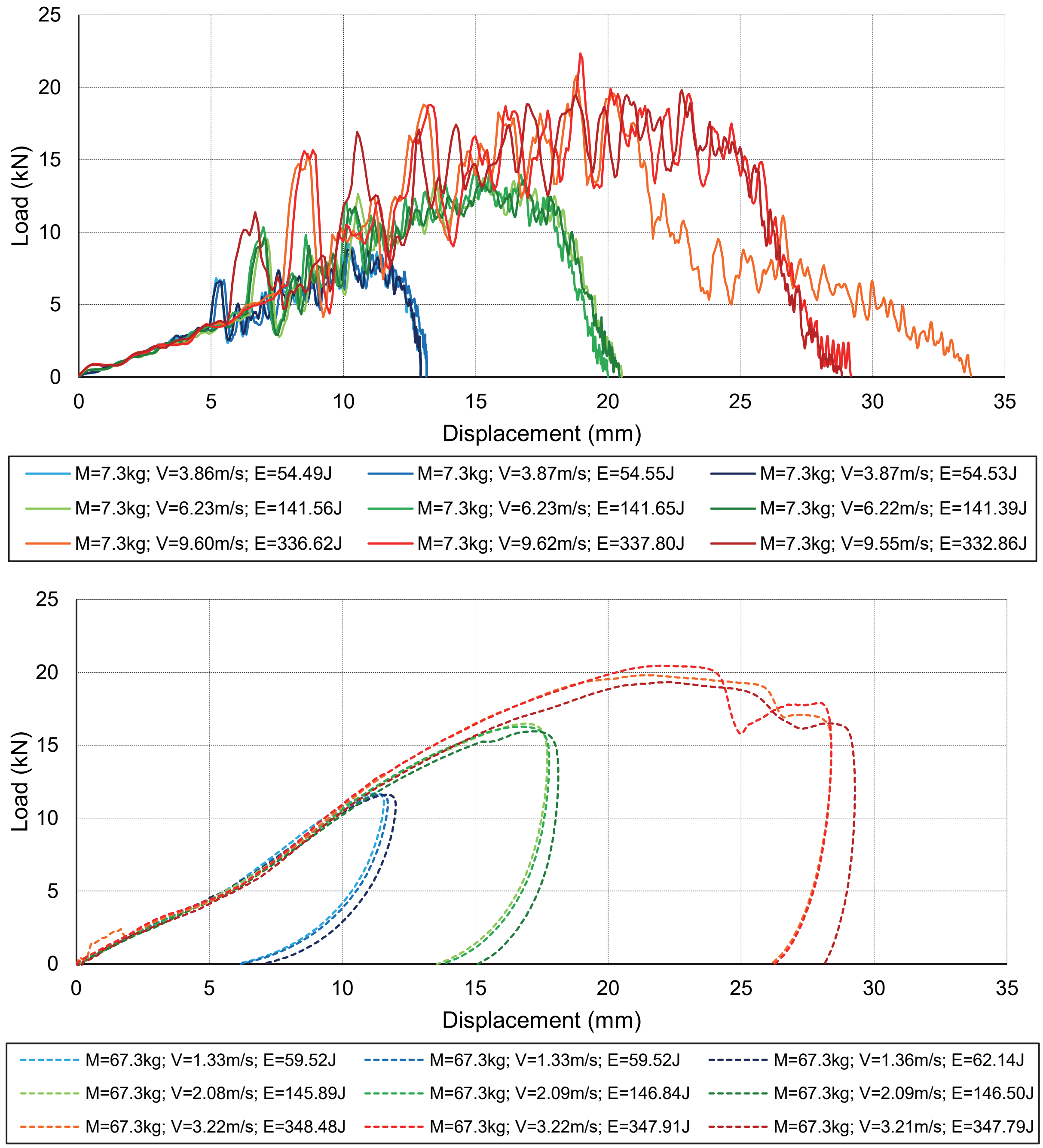
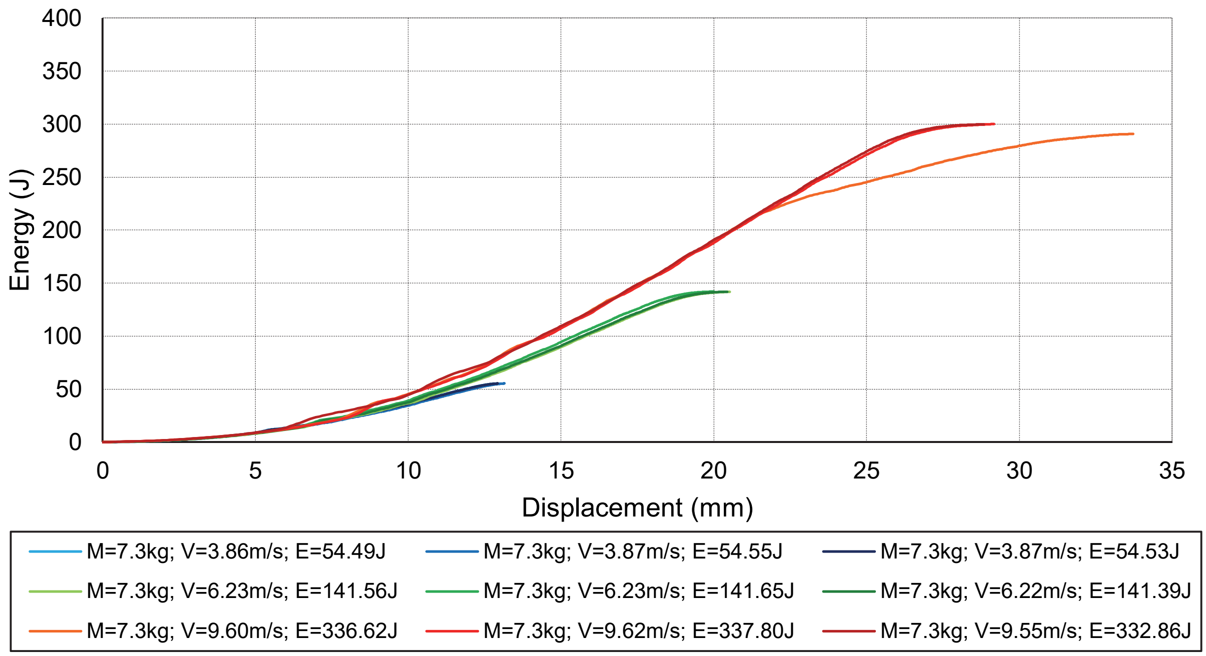



**Figure 7:** Load vs displacement curves for the tested materials.

Unlike the common FRP composites, which exhibit a complete brittle fracture, the fully PP composite showed a ductile behavior and a developed extended plasticity without a crack tip. The linearity of the load deflection records and the features of the fracture surface put in evidence this behavior. The load increased non-linearly without drastic drop because no sample failure can be observed.

### 4.1 Effects of the impact energy, of the impact velocity and of the impactor mass

It has been possible to investigate the effect of the impact energy at constant impactor mass and, conversely, the influence of the mass of the impactor at constant impact energy was investigated analyzing the experimental results. In Figure 8, the results of the impact tests are summarized in terms of energy-displacement curves. The contact force (Figure 7), the maximum displacement and the absorbed energy (Figure 8) increases with the impact energy. The curves tend to follow the same behavior of the curves with lower energy, then the deformation increases due to the higher energy involved for the higher impact energy levels.



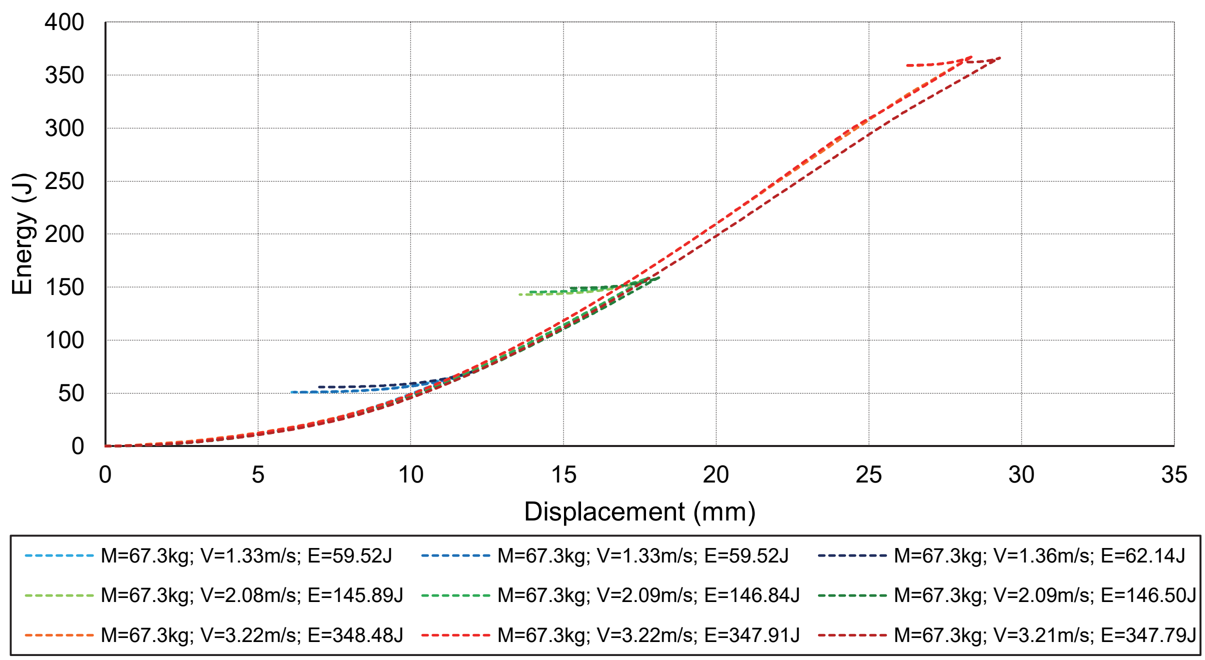




**Figure 8:** The energy-displacement histories for the tested material.

The yarn sliding appears to be one of the most significant damage mechanisms for the first plies. A cross shape sliding can be noticed for the primary yarns (i.e. the yarns situated directly under the impactor [48]). The observed damage is represented by a scheme in Figure 9-a for 0-90° oriented plies and by the image of a PURE specimen after the test in Figure 9-b.

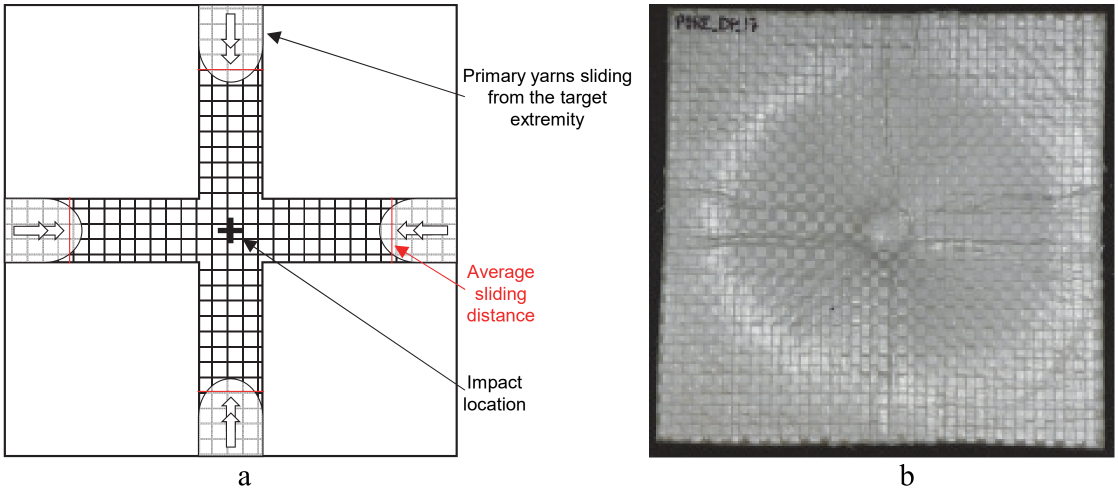



**Figure 9:** Damage of thermoplastic fabrics; a) schematic [47], b) a PURE specimen after the test (test conditions: mass 67.3 kg, velocity 2.09 m/s, energy 146.5 J).

The yarn sliding is visible from the target boundary to the impact location. It is interesting to observe as the sliding distance is very similar in the weft and the warp directions.

Other damage mechanisms can be observed in addition to the principal yarn sliding. The impact energy is spent mostly for delamination with the lighter impactor mass. Conversely, the impact energy is spent mostly for the fibers fracture around the impact point (in a zone with a radius of approximately 20 mm) for the heavier impactor mass. These behaviors depend on the difference between the inertia forces of the impactors with a mass of 7.3 and a mass of 67.3 kg. Despite the velocity relations, to stop the lightest impactor seems to be easier than to stop the heaviest one. The tests conducted at the higher velocity and with the lowest mass produce more dynamic vibrations than the opposite condition (lower velocity and the highest mass) (see the fluctuation of the force diagrams in figure 7a in comparison with the smoothness of the force curves in figure 7b). These high frequency vibrations overcome the shear forces by breaking the molecular chain of the polypropylene in each interface layer. This causes the delamination phenomenon. However, in the tests with the heaviest mass, a smaller amount of energy than in the test with the lightest mass is converted into vibrations. Consequently, the kinetic energy breaks the fibers with a resultant fiber damage. Another significant energy absorption mechanism may be due to different type of contact friction between the yarns: weft/warp yarn crossings, contacts between the plies and contact between the impactor and the first ply [49]. A cap formation can be observed in the rear skin of the specimens, as partially shown in Figure 10.

Previous studies [50-53] have shown the influence of processing parameters, such as compaction temperature and pressure, on the mechanical properties and on the absorbed impact energy of self-reinforced polypropylene composites. According to Barany *et al.* [50-51] at low temperatures, the failure occurs typically by delamination and fiber pullout, whereas at high values, the delamination was restricted and the sheet showed markedly lower values of perforation energy. As indicated by Alcock *et al.* [53] specimen consolidated at lower temperature and pressure shows large amounts of fibrillation and delocalized deformation giving a circular indentation, whereas specimen consolidated at higher temperature and pressure, as in this study, shows very localized damage and breakage along tape boundaries giving a characteristic star-shaped indentation.

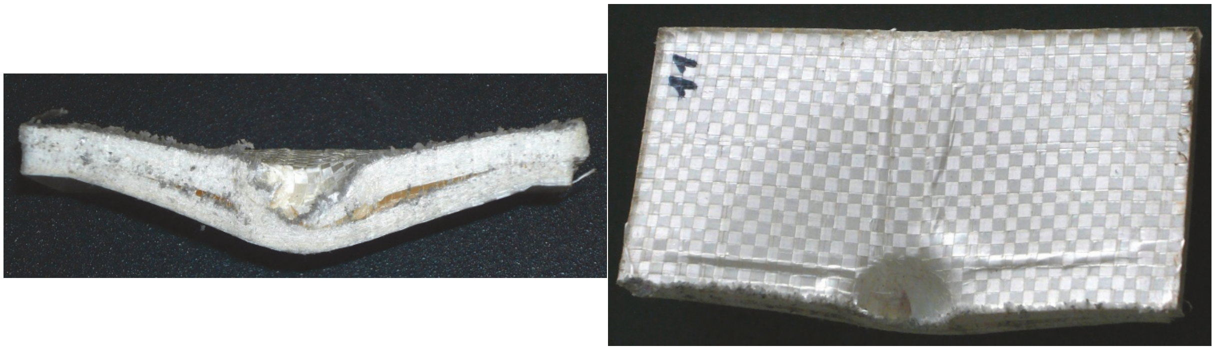


**Figure 10:** A section of a specimen after the drop dart test (test conditions: mass 7.3 kg, velocity 9.54 m/s, energy 332.1 J). The specimen was cut in its middle layer.

A series of parameters were calculated from the experimental results in order to study the impact behavior of the material object of this work. In particular, the peak values of the contact force, the deflection of the specimen, the stiffness of the specimen, the energy absorbed by the specimen and the contact time were considered. The average values and the standard deviations of these parameters obtained in the experimental tests are summarized in Table 3. The stiffness was evaluated as the slope of the first linear part of the load-displacement curve. The obtained values are rather comparable considering the same impact conditions. The data are more scattered increasing the impact velocity, in particular considering the values of the load and of the deflection. Consequently, the stiffness values were also scattered at the highest velocities. The effect of the impact mass can be observed clearly from the diagrams of Figures 11 to 13 each of them is reporting the curves obtained from the tests at the same impact energy. The difference in terms of stiffness between the tests performed with the two mass values is much more prominent at the lowest impact energy. The trends of the first part of the force-displacement curves are more similar increasing the kinetic energy. In all cases, a higher stiffness was obtained with the highest mass.

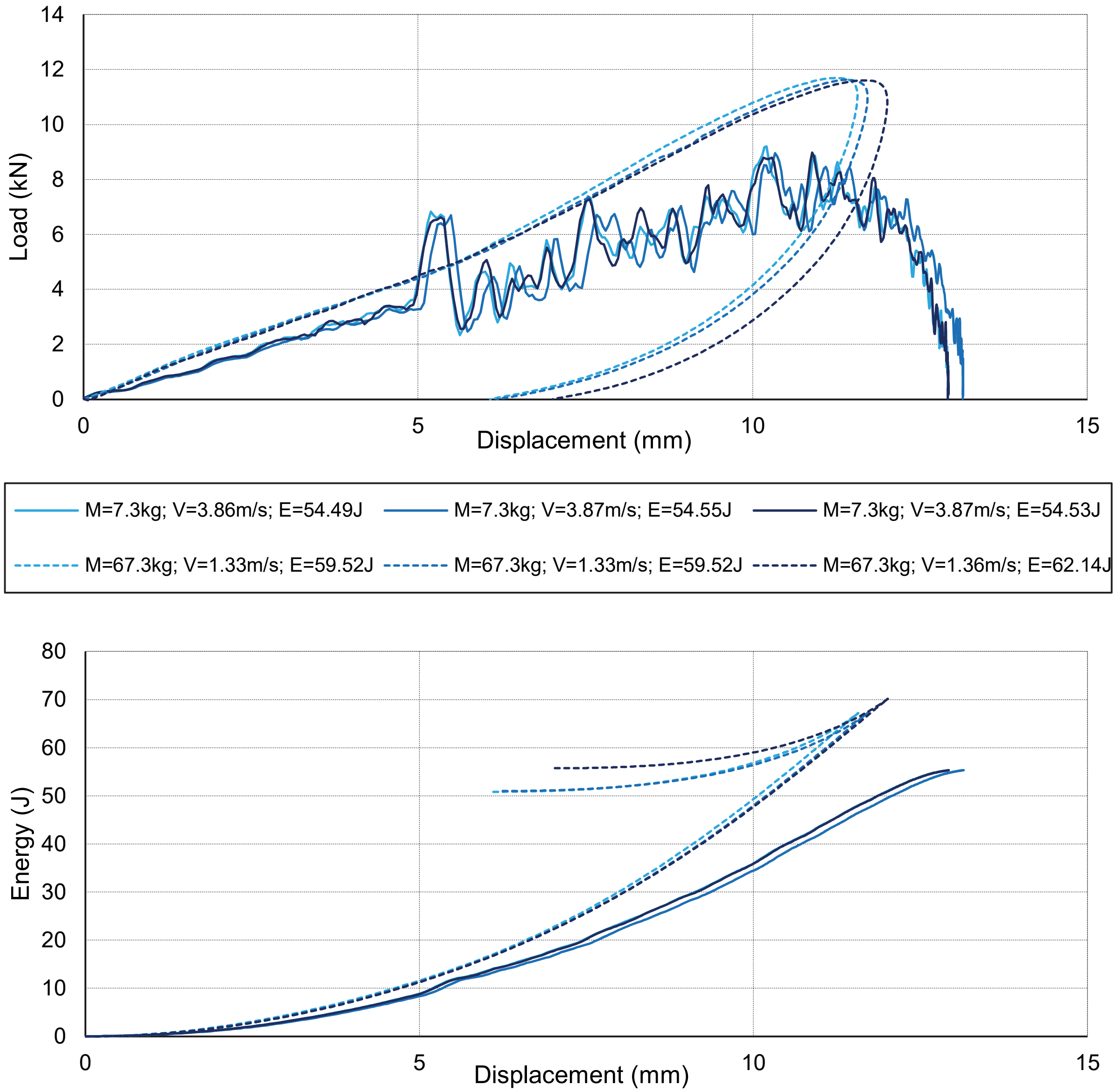



**Figure 11:** The contact force-displacement and the energy-displacement histories at constant impact energy ≈ 57 J.

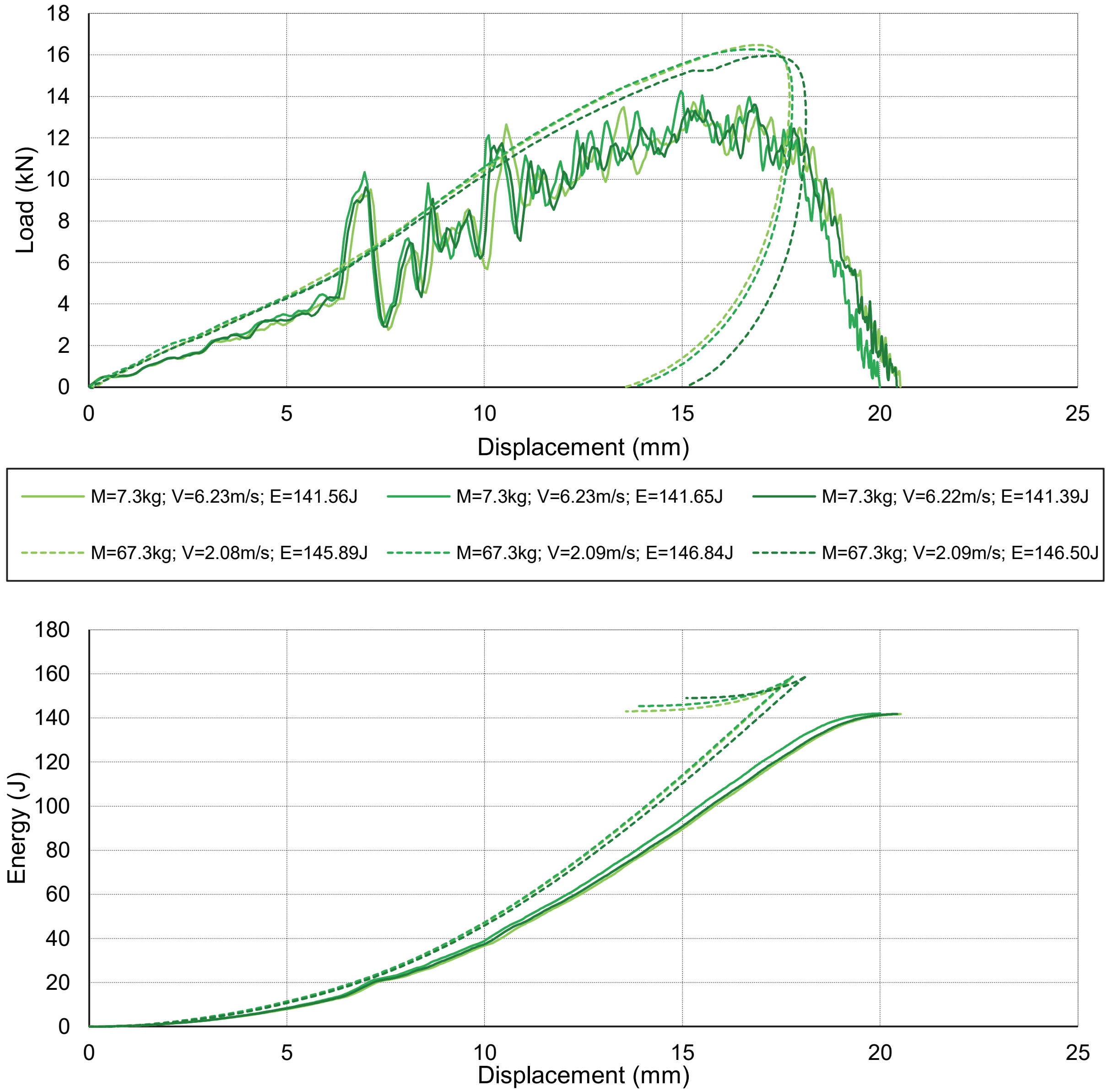



**Figure 12:** The contact force-displacement and the energy-displacement histories at constant impact energy ≈ 144 J.

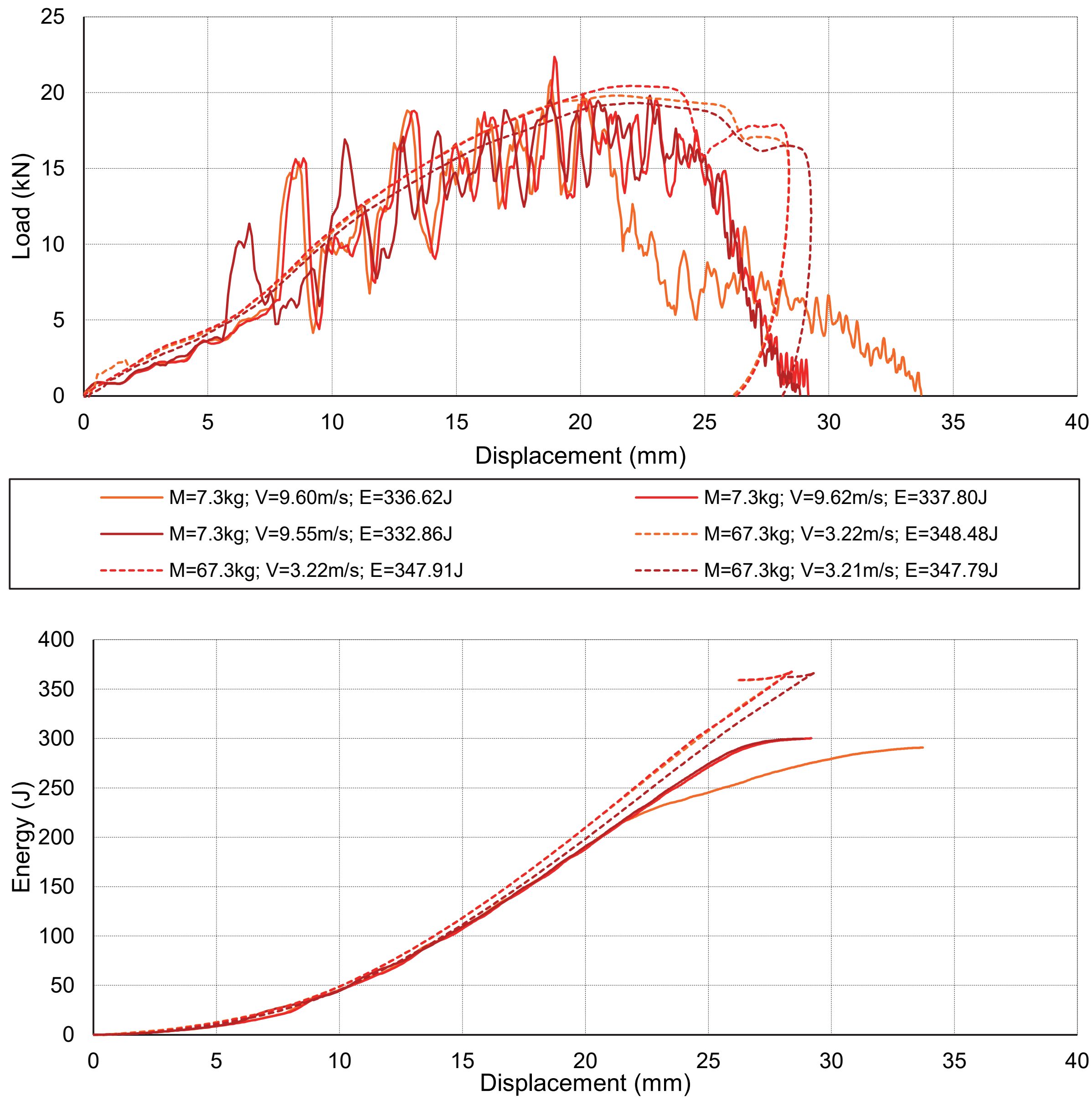



**Figure 13:** The contact force-displacement and the energy-displacement histories at constant impact energy ≈ 342 J.

| | | Impact energy (J) | | |
|---|---|---|---|---|
| | Mass (kg) | Level 1 (~57) | Level 2 (~144) | Level 3 (~342) |
| Max. contact force (kN) | 7.3 | 9.0±0.1 | 13.9±0.3 | 21±1.3 |
| | 67.3 | 11.6±0.0 | 16.2±0.3 | 19.9±0.6 |
| Max. deflection (mm) | 7.3 | 13±0.1 | 20.3±0.3 | 30.6±2.7 |
| | 67.3 | 11.8±0.2 | 17.9±0.2 | 28.7±0.5 |
| Stiffness (N/mm) | 7.3 | 739±16 | 662±34 | 782±136 |
| | 67.3 | 994±17 | 865±20 | 810±72 |
| Contact time (ms) | 7.3 | 7.1±0.1 | 6.4±0.0 | 6.3±0.4 |
| | 67.3 | 24.8±0.2 | 22.3±0.4 | 21.4±0.4 |
| Absorbed energy (J) | 7.3 | 55.3±0.0 | 141.8±0.1 | 296.9±5.3 |
| | 67.3 | 68.2±1.7 | 158.3±0.9 | 367.1±0.9 |

**Table 3:** Parameters obtained with the experimental results: average values and standard deviations.

The difference of the contact times (Table 3) between the specimens impacted with the two different masses shows the energy transfer speeds. Transferring the energy in a shorter time implies an increase in the magnitude of the impulsive forces. More intense pulse forces cause more delamination and higher frequency vibrations than with slow impacts at the same impact energy level. A higher amount of the internal damages has also influence on the stiffness of the specimen as discussed in [54-55] and as evidenced in the following. Moreover, the maximum load tends to increase almost linearly with the growth of the absorbed energy as shown in Figure 14.

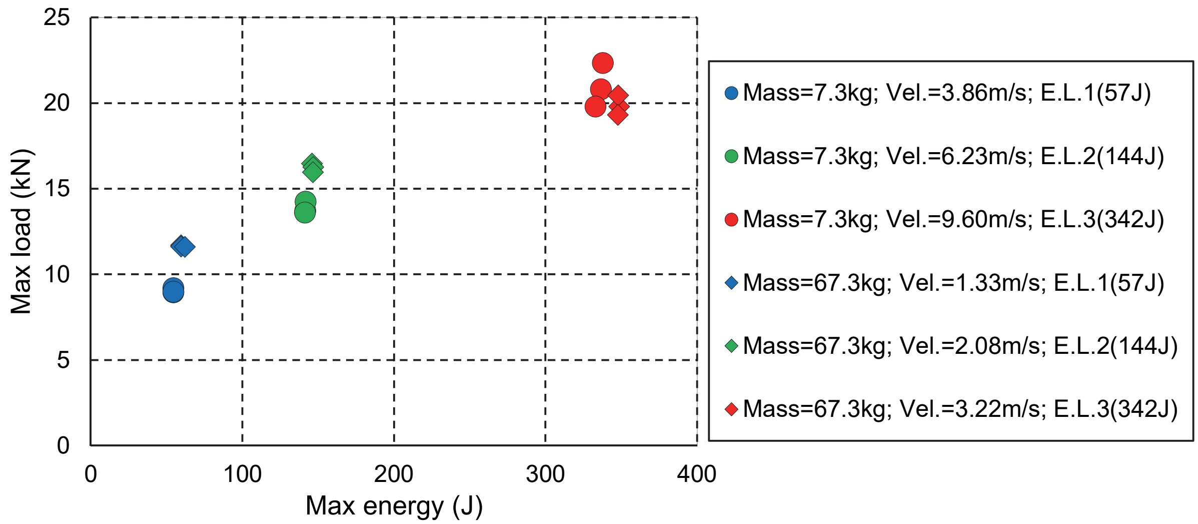



**Figure 14:** Trend of the maximum load as a function of the absorbed energy.

The effects of the impact mass and of the impact velocity on the maximum load, on the absorbed energy and on the stiffness are shown in Figures 15 and 16. With an increment in the impact energy the increase of the maximum load due to a variation of  the impactor mass is less evident. A change of trend was recorded for the highest energy level. An opposite behaviour was observed considering the velocity influence: with an increment in the impact velocity there was a decrease of the maximum load. This trend tends to reverse for the maximum energy level considered. The same analyses have been conducted for the absorbed energy and the stiffness varying both the mass and the velocity. The stiffness is influenced by the velocity and by the amount of the internal damage as discussed before and in concordance with has been illustrated in [47, 54-55]. Opposite behaviours were noted also in such cases. An increase of the absorbed energy and of the stiffness is evident increasing the mass, whereas higher velocity implies lower energies and stiffness.

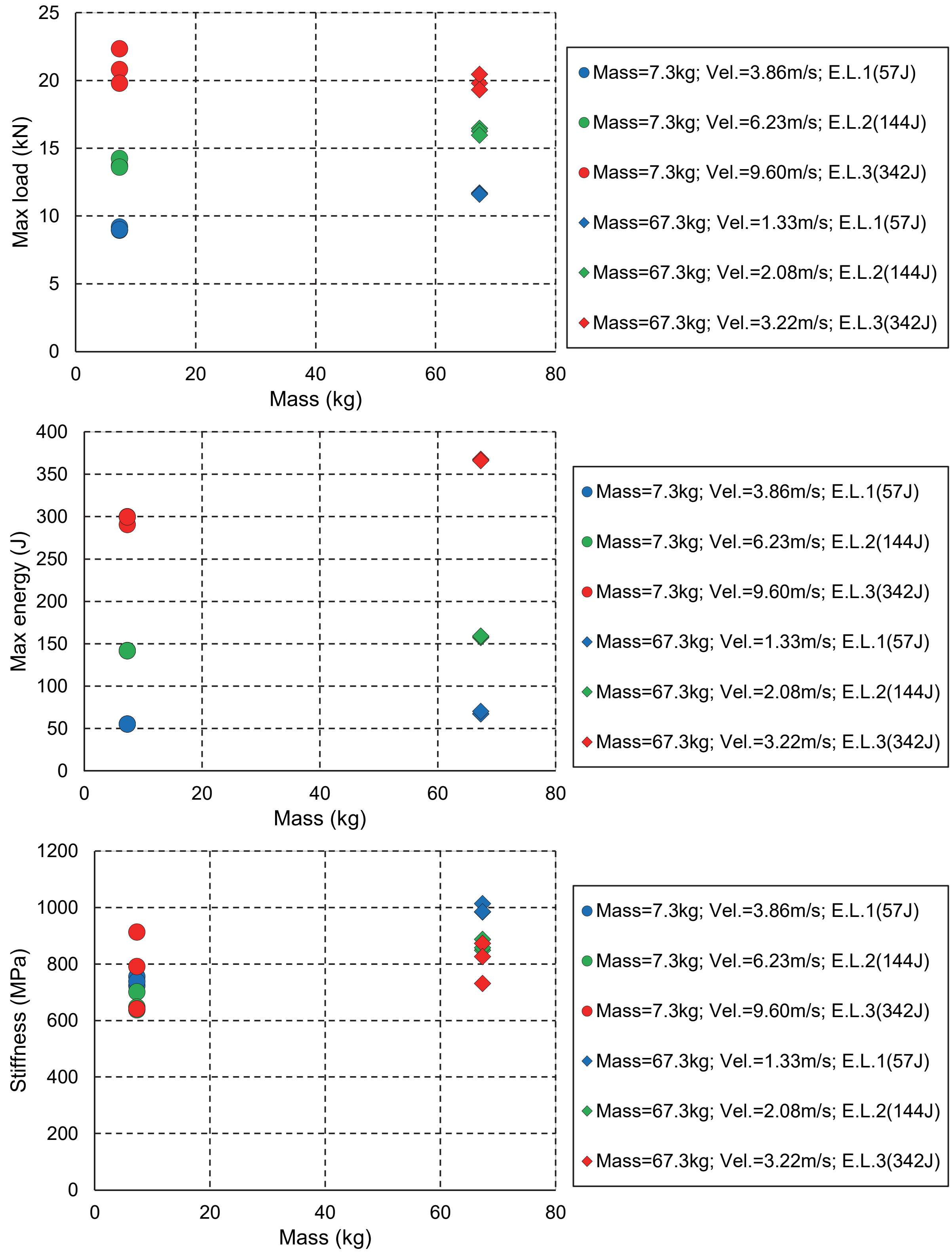



**Figure 15:** The effect of the impact mass on the maximum force, on the absorbed energy and on the stiffness.

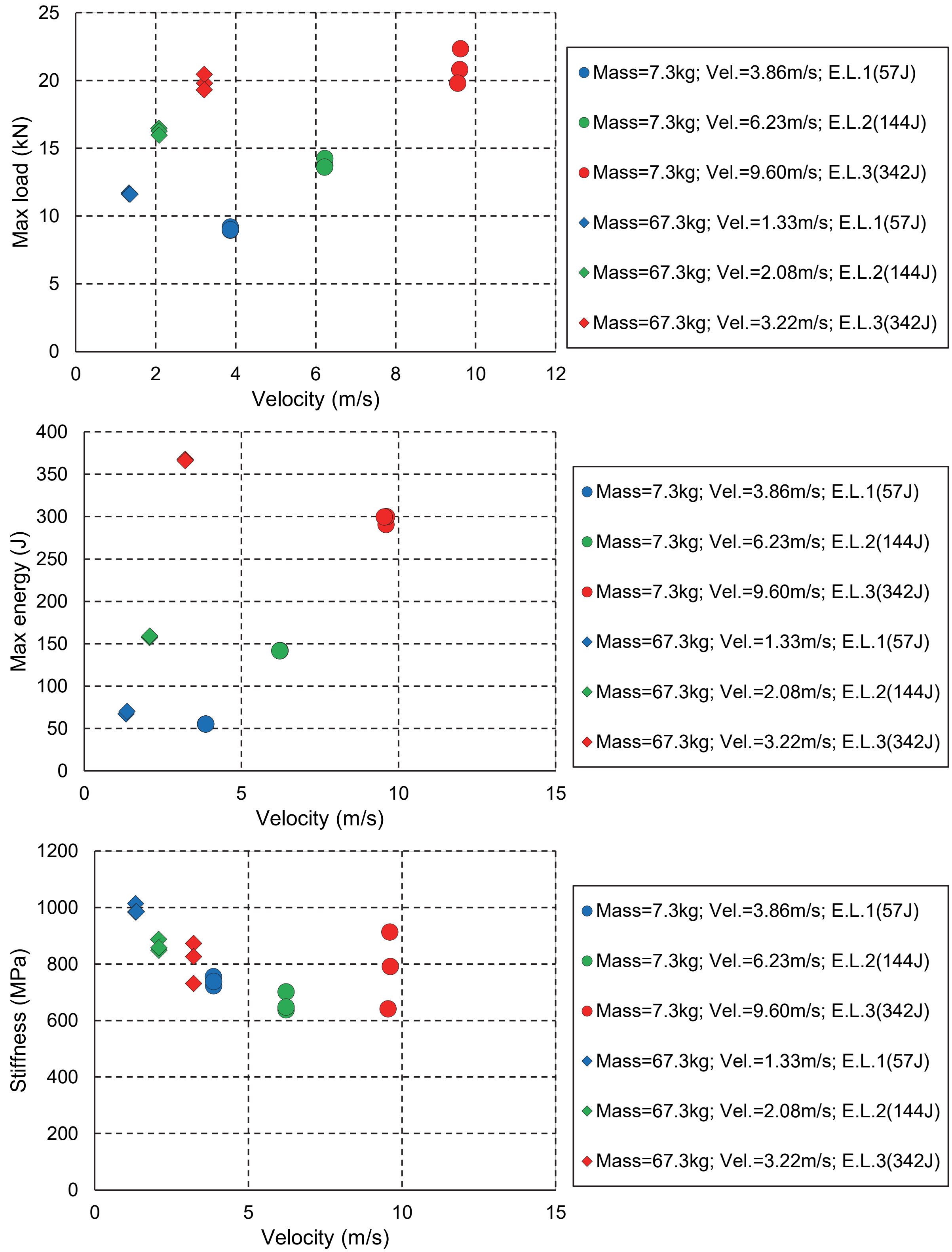



**Figure 16:** The effect of the velocity on the maximum force, on the absorbed energy and on the stiffness.

## 5 CONCLUSIONS

This study presents the main results of an experimental investigation on the impact response of a fully thermoplastic composite laminates overlaying 0-90° plain weaves. Three different impact energies were considered in the study varying both the impactor mass and the initial velocity. The fully PP composite showed a ductile behavior and developed extended plasticity without a crack tip unlike common FRP composites, where complete brittle fracture is generally exhibited. This was deduced from the linearity of the load-deflection records and with the features of the fracture surface. The load increased non-linearly and displayed no drastic drop because no samples failure, and in particular no sample perforation, was observed.

The main damage mechanisms observed were yarn sliding, delamination and fibres fracture. Only rebounding and penetration were noted as impact behaviour. No perforation was obtained, probably, due to the high thickness of the laminate. The tests were generally affected by a slip phenomenon between the specimens and the clamping device, due to the particular shrinkage phenomenon of the examined material.

The maximum load tends to increase almost linearly with the growth of the absorbed energy. The percentage of the increase for the maximum load varying the impactor mass tends to decrease increasing the impact energy. For the highest energy even a change of trend was recorded.

Fot what concerns the velocity influence, an opposite behaviour was observed: increasing the velocity there was a decrease of the maximum load that tends to zero and to reverse for the maximum energy analysed. The same analyses have been conducted for the absorbed energy and the stiffness varying both the mass and the velocity. Opposite behaviours were noted also in such cases: increasing the mass it was evident an increase of the absorbed energy and of the stiffness, whereas higher velocity implied lower energies and stiffnesses.

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## REFERENCES


[1] G.Belingardi, G.Chiandussi, Vehicle crashworthiness design–general principles and potentialities of composite material structures. In: *Impact engineering of composite structures*, S.Abrate (editor), Springer, Wien, pp 193–264, 2011.

[2] G.Belingardi, A.Scattina, Experimental investigation on the bending behaviour of hybrid and steel thin walled box beams—The role of adhesive joints, *International Journal of Adhesion and Adhesives*, 40, 31-37, 2013

[3] A.Airale, M.Carello, A.Scattina, Carbon fiber monocoque for a hydrogen prototype for low consumption challenge, *Materialwissenschaft und werkstofftechnik*, 42(5), 386-392, 2011.

[4] G.Belingardi, S.Boria, J.Obradovic, Energy absorbing sacrificial structures made of composite materials for vehicle crash design, In: *Dynamic Failure of Composite and Sandwich Structures, Solid Mechanics and Its Applications*, Ed. S.Abrate et al., Springer, 192, 577-609, 2013.

[5] R.Mantena, R.Mann, C.Nori, Low-velocity impact response and dynamic characteristics of glass-resin composites, *Journal of Reinforced Plastics and Composites*, 20, 513-533, 2001.

[6] P.O.Sjoblom, J.T.Hartness, T.M.Cordell, On Low-Velocity Impact Testing of Composite Materials, *Journal of Composite Materials*, 22(1), 30-52, 1988.

[7] W.J.Cantwell, J.Morton, The impact resistance of composite materials- a review, *Composites*, 22(5), 347-362, 1991.

[8] S.Abrate, Impact on laminated composite materials, *Applied Mechanics Reviews*, 44, 155-190, 1991.

[9] M.O.W.Richardson, M.J.Wisheart, Review of low-velocity impact properties of composite materials, *Composites A*, 27, 1123-1131, 1996.

[10] T.Anderson, E.Madenci, Experimental investigation of low-velocity impact characteristics of sandwich composites*,* *Composite Structures*, 50, 239-247, 2000.

[11] V.Tita, J.Carvalho, D.Vandepitte, Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches, *Composite Structures*, 83(4), p. 413-428, 2008.

[12] J.Wang, A.M.Waas, H.Wang, Experimental and numerical study on the low velocity impact behavior of foam-core sandwich panels, *Composite Structures*, 96, 298-311, 2013.

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

[14] S.Abrate, Impact on Composite Structures, Cambridge University Press, 2005.

[15] Dynamic Deformation, Damage and Fracture in Composite Materials and Structures, V.Silberschmidt (editor), Woodhead Publishing, 2016.

[16] S.Abrate, Impact on laminated composite materials: Recent advances, *Applied Mechanics Reviews*, 47, 517-544, 1994.

[17] Y.Shi, T.Swait, C.Soutis, Modeling damage evolution in composite laminates subjected to low velocity impact, *Composite Structures*, 94, 2902-2913, 2012.

[18] L.Raimondo, L.Iannucci, P.Robinson, P.T.Curtis, A progressive failure model for mesh-size-independent FE analysis of composite laminates subject to low-velocity impact damage, C*omposites Science and Technology*, 72, 624-632, 2012.

[19] E.H.Kim, M.S.Rim, I.Lee, T.K.Hwang, Composite damage model based on continuum damage mechanics and low velocity impact analysis of composite plates, *Composite Structures*, 95, 123-134, 2013.

[20] M.B.P.Bussadori, K.Schuffenhauer, A.Scattina, Modelling of CFRP crushing structures in explicit crash analysis, *Composites Part B, Engineering*, 60, 725-735, 2014.[21] S.Abrate, Modelling of impacts on composite structures, *Composite Structure*, 51, 129-138, 2001.

[22] M.F.S.F.de Moura, A.T.Marques, Prediction of low velocity impact damage in carbon-epoxy laminates, *Composite Part A*, 33(3), 361-368, 2002.

[23] S.M.R.Khalili, M.Soroush, A.Davar, O.Rahmani, Finite element modeling of low-velocity impact on laminated composite plates and cylindrical shells, *Composite Structures*, 93(5), 1363-1375, 2011.

[24] S.Xu, P.H.Chen, Prediction of low velocity impact damage in carbon/epoxy Laminates, *Procedia Engineering*, 67, 489-496, 2013.

[25] N.H.Nash, T.M.Young, P.T.McGrail, W.F.Stanley, Inclusion of a thermoplastic phase to improve impact and post-impact performances of carbon fibre reinforced thermosetting composites-A review, *Materials and Design*, 85, 582-597, 2015.

[26] J.P.Dear, S.A.Brown, Impact damage process in reinforced polymeric materials, *Composites: Part A*, 34, 411-420, 2003.

[27] J.F.Kalthoff, On the Measurement of dynamic fracture toughness-a review of recent work, *International Journal of Fracture*, 27(3), 277-298, 1985.

[28] A.Pavan, S.Draghi, Further experimental analysis of the dynamic effects occurring in three-point bending fracture testing at moderately high loading rates (1 m/s) and their simulation using an ad hoc mass spring-dashpot model, in *ESIS Publication 27: Fracture of Polymers, Composites and Adhesives*, J. G. Williams, A. Pavan (eds.), Elsevier, 347-361, 2000.

[29] J.G.Williams, G.C.Adams, The analysis of instrumented impact tests using a mass-spring model, *International Journal of Fracture*, 33(3), 209-222, 1987.

[30] S.Boria, A.Scattina, G.Belingardi, Experimental evaluation of a fully recyclable thermoplastic composite, *Composite Structures*, 140, 21-35, 2016.

[31] G.Belingardi, M.P.Cavatorta, D.S.Paolino, Repeated impact response of hand lay-up and vacuum infusion thick glass reinforced laminates, *International Journal of Impact Engineering*, 35, 609–619, 2008.

[32] D.Liu, Characterization of impact properties and damage process of glass/epoxy composite laminates, *Journal of Composite Materials*, 38, 1425-1442, 2004.

[33] J.K.Kim, D.B.Mackay, Y.W.Mai, Drop-weight impact damage tolerance of CFRP with rubber-modified epoxy matrix, *Composites*, 24 (6), 485-494, 1992.

[34] ASTM D5628-96. Standard test method for impact resistance of flat, rigid plastic specimens by means of a falling dart (tup or falling mass).

[35] W.J.Cantwell, J.Morton, The impact resistance of composite materials-a review, *Composites*, 22 (5), 347-362, 1991.

[36] D.Liu, B.B.Raju, X.Dang, Impact perforation resistance of laminated and assembled composite plates, *International Journal of Impact Engineering*, 24, 733-746, 2000.

[37] M.T.H.Sultan, A.Hodzic, W.J.Staszewski and K. Worden, A SEM-Based Study of Structural Impact Damage, *Applied Mechanics and Materials*, 24-25, 233-238, 2010.

[38] J.M.Duell, Impact Testing of Advanced Composites, in *Advanced Topics in Characterization of Composites*, 2001.

[39] Z.Aslan, R.Karakuzu, B.Okutan, The response of laminated composite plates under low- velocity impact loading. *Composite Structures*, 59(1):119-1278, 2003.

[40] C.Soutis, P.T.Curtis, Prediction of the post-impact compressive strength of CFRP laminated composites. *Composites Science and Technology*, 56(6), 677-684, 1996.

[41] M.O.W.Richardson, M.J.Wisheart, Review of low-velocity impact properties of composite materials. *Composites Part A: Applied Science and Manufacturing*, 27(12), 1123-1131, 1996.

[42] W.J.Cantwell, J.Morton, The impact resistance of composite materials-a review. *Composites*, 22(5), 347-362, 1991.

[43] Y.Li, Y.-W.Mai, L.Ye, Effects of fibre surface treatment on fracture-mechanical properties of sisal-fibre composites. *Composite Interfaces*, 12, 141-163, 2005.

[44] L.Iannucci, R.Dechaene, M.Willows, J.Degrieck, A failure model for the analysis of thin woven glass composite structures under impact loadings. *Computers & Structures*, 79(8), 785-799, 2001.

[45] M.Aktas, C.Atas, B.M.Icten, R.Karakuzu, An experimental investigation of the impact response of composite laminates, *Composite Structures*, 87, 307-313, 2009.

[46] E.Erbil, Impact loading in laminated composites, M.Sc. Thesis in Mechanical Engineering, Dokuz Eylül University, 2008.

[47] N.P.Bansal, J.Lamon, Ceramic matrix composites: materials, modeling and technology, Wiley, 2004.

[48] A.Kolopp, S.Rivallant, C.Bouvet, Experimental study of sandwich structures as armour against medium-velocity impacts, *International Journal of Impact Engineering*, 61, 24-35, 2013.

[49] I.H.Choi, Contact force history analysis of composite sandwich plates subjected to low-velocity impact, *Composite Structures*, 75(1-4), 582-586, 2006.

[50] T.Barany, J.Karger-Kocsis, T.Czigany, Development and characterization of self-reinforced poly(propylene) composites: carded mat reinforcement, *Polymers for Advanced Technologies*, 17 (9-10), 818-824, 2006.

[51] T.Barany, A.Izer, J.Karger-Kocsis, Impact resistance of all-polypropylene composites composed of alpha and beta modifications, *Polymer Testing*, 28, 176-182, 2009.

[52] B.Alcock, N.O.Cabrera, N.-M.Barkoula, T.Peijs, Low velocity impact performance of recyclable all-polypropylene composites, *Composites Science and Technology*, 66, 1724-1737, 2006.

[53] B.Alcock, N.Cabrera, N.-M.Barkoula,J. Loos, T.Peijs, The mechanical properties of woven tape all-polypropylene composites, *Composites: Part A*, 38, 147–161, 2007.

[54] B.M. Demerath, Low velocity impact damage assessment in IM7/977-3 cross-ply composites using 3D computed tomography, MS thesis, University of Iowa, 2015.

[55] N.Razali, M.T.H. Sultan, F. Mustapha, N. Yidris, M.R. Ishak, Impact Damage on Composite Structures – A Review, *The International Journal Of Engineering And Science*, 3(7), 8-20, 2014.



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