Influence of impact velocity on impact behaviour of hybrid woven-fibers reinforced PEEK thermoplastic laminates

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A B S T R A C T

This study aims at examining the impact behavior of hybrid carbon and glass fibers woven-ply reinforced PolyEther Ether Ketone (PEEK) thermoplastic quasi-isotropic laminates. An instrumented Charpy pendulum is specifically designed to estimate its capability to perform low velocity impact tests. Through the comparison of different impact methods (Quasi-static indentation tests, Charpy and drop tower impacts), the influence of impact velocity on the impact behavior of this hybrid composite material is investigated. From the obtained results, it appears that the macroscopic impact response is similar in terms of force-displacement response. Indeed, the impact velocity is significantly higher (2.5 times higher) with falling weight impact testing. In PEEK-based laminates whose mechanical behaviour is time-dependent, slow loading rates (e.g. Charpy impact testing) are instrumental in ruling the dissipated energy (+20% at 35 and 40J) as well as in increasing the permanent indentation (1.6 times higher) that is always higher than the Barely Visible Impact Damage.

1. Introduction

The effects of impact on fiber-reinforced composites is widely addressed in the literature and yet analysing the phenomenon and relating effects to the forces acting and the materials' properties, in order to predict the outcome of a particular event, can be very difficult [1]. Depending on the impact conditions, it usually results in deformation, permanent damage, complete penetration of the body struck or fragmentation of the impacting or impacted body, or both. For fibre-reinforced composite materials, it is permanent damage, possibly subsurface and barely visible, penetration and fragmentation, that are of interest. There are various ways of analysing the impact process; in terms of the energy deposited and gross damage produced, micro energy dissipation or by considering the stresses acting on flaws in the material and the effects that are generated. The latter method, which is known as fracture mechanics, is extensively employed with metals but will only be alluded to here. In practice, the impact behaviour of composites merges into the general area of damage mechanics.

There are many factors influencing the impact resistance and damage tolerance of fiber-reinforced composites [2]: fibers architecture, resin toughness, hygrothermal and temperature conditions, stacking sequence, fiber hybridization, matrix hybridization, impactor geometry (size, shape, and mass), impact-loading type (monotonic or repeated), or impact velocity. All these factors may rule the impact behaviour of composite materials in terms of macroscopic force-displacement response, dissipated energy, impact-induced damage mechanisms and permanent indentation.

When it comes to the impact behaviour of composite laminates, the role of the matrix is instrumental; protecting the fibre, transferring stresses and, in some cases, alleviating brittle failure by providing alternative paths for crack growth [1]. It is therefore required to evaluate the influence of impact velocity on impact response in terms of dissipated energy as well as impact-induced damages. In a previous study, impact tests were performed on hybrid carbon and glass fibers woven-ply reinforced PolyEther Ether Ketone (PEEK) thermoplastic (TP) laminates using a drop tower system with a 16 mm diameter, 2 kg impactor, complying with the requirements of the Airbus Industries Test Method (AITM 1-0010) [3]. The effect of temperature on the impact behaviour and damage tolerance of this composite material (same material as the one investigated in this study) was examined. From the results, it appears that these composite materials have a very good impact behaviour (high permanent indentation, good impact detectability and reduction delamination), and a high degree of damage tolerance, even at temperatures close to their glass transition temperature Tg.

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Regarding certification of aircraft using composite structures, critical components must be fatigue tested with previously inflicted flaws to account for a worst-case condition [4]. Impact damage is one type of flaw required in test components to simulate real world impacts during the manufacturing, the maintenance and operational phases of aircraft life.

1.1. Low-velocity impact behaviour characterization

Impact testing machines usually include vertical drop towers and spring loaded impact guns. Vertical drop towers are bulky, difficult to position, and because of freefalling impactors provide inexact point and shape of impact. Vertical drop towers cannot be used when a horizontal impacting direction is required. Horizontal spring loaded impact guns have difficulty with containment of the reaction force as well as double impact issues. In addition, they are difficult to be instrumented. Pendulum type impactors are typically used for Charpy and Izod small coupon fatigue testing. They are not designed for imparting impact damage on large aircraft components, and cannot be manipulated to specific locations on the large airframe structures.

These various types of impact testing machines differ from one another primarily in the shape of the specimen, in the way in which the specimen is held at the moment of fracture, and in the shape of the hammer striking specimen [5]. The Izod and Charpy tests have been used for many years to assess the impact performance of metals particularly with respect to the brittle/ductile transition temperature and notch sensitivity [1], but the drop tower is still the most commonly used to conduct impact tests on composite laminates [3,6].

Quasi-static indentation tests conducted on uniaxial testing machines are based on specific tooling (indentor and supporting frame). The obtained results are usually treated as very low velocity impacts when examining the effect of impact velocity on damage at a later stage.When dynamic effects in the structure do become important, the impact force and the resulting peak values of stresses and strains in the structure typically become larger than they would be for a given impact energy under quasi-static loading [7]. Compared to thermosetting-based composites, these dynamic effects are expected to have a significant influence on the impact behaviour of thermoplastic-based composites due to their time-dependent mechanical behaviors [8,9].

Most of the studies dealing with the impact behaviour of thermoplastic laminates are conducted by using an instrumented, tailor-made, drop-weight test rig [8–11]. They are restricted to low impact velocities but high incident kinetic energies are achieved through the use of high masses. Impact velocities regulated by selected drop heights usually vary between 2 m/s and 8 m/s. The force-displacement curves are classically obtained from a load sensor positioned between the impactor head and the drop-weight body. In the current state of the art, pendulum-type impact devices are mostly used to carry out destructive testing of materials on V-notched specimens. These are the pendulums for carrying out characterizations of materials using the Charpy method, which measures a specimen's resistance to breakage when it is impacted using a pendulum with a hammer at its tip. The hammer is instrumented and the device is equipped with a data acquisition system.

Instrumented Charpy pendulum impact tests have been conducted on V-notched composite specimens [12–17]. Early in the seventies, Adams et al. have used an instrumented Charpy impact-testing machine. They have observed that the maximum impact forces and the impact moduli were determined, and compared to the corresponding values from quasi-static tests [17]. The maximum force is independent of loading rate, while the impact modulus is significantly less than the static flexural modulus. The various composites were found to be severely degraded by the low-level impacts. More recently, a Charpy pendulum was modified by Meola et al. to conduct impact tests on rectangular specimens [18,19].

Table 1
A few properties of woven carbon and glass fibers reinforced PEEK elementary ply at RT.

	Carbon/PEEK	Glass/PEEK
E_x (GPa)	60	22
E_y (GPa)	60	20
G_{xy} (GPa)	4.8	6.55
ν_{xy}	0.04	0.04
Tensile strength (warp) (MPa)	963	1172
Compressive strength (warp) (MPa)	725	1103
Nominal ply thickness (mm)	0.31	0.08

Table 2
Mechanical properties in tension and compression of unnotched C/G/PEEK quasi-isotropic laminates at room temperature.

	E_x (GPa)	σ_x^u(MPa)	ε_x^u (%)
Tension	52.57±0.58	784±22	1.52±0.04
Compression	49.25±0.50	573±13	1.75±0.07

1.2. Objectives of the study

Through the comparison of low-velocity impacts tests conducted with a drop tower and a modified Charpy pendulum, this work aims at investigating the influence of loading conditions (impact velocity) on the impact behaviour of hybrid thermoplastic laminates. The impact behaviour will be discussed in terms of macroscopic impact response (force-displacement curve), dissipated energy and permanent indentation. The time-dependent behaviour of thermoplastic-based composites is expected to reflect on the impact behaviour depending on impact velocity. The discussion will be supported by microscopic observations of impacted specimens.

2. Materials and experimental set-up

2.1. Materials and specimen

The composite materials under investigation consists of 14 carbon-PEEK woven plies with two outer glass-PEEK woven plies whose aim is to protect the carbon core (electrical protection) [3]. The laminated plates are made up of carbon (Tenax -E HTA40 3K)–PEEK 5HS (Harness Satin) woven plies with a glass–PEEK ply on each surface and obtained by thermo-stamping process (Tables 1 and 2). The stacking sequence is balanced and symmetric (Fig. 1): $[(0/90)_G, [(0/90), (\pm 45)]_3, (0/90)]_s$ (with G index for glass fibers ply). The laminates average thickness is about 4.5 mm. Test specimens are rectangular plates whose dimensions are 150 × 100 mm^2 cut by water jet from 600 × 600 mm^2 plates. Four specimens were impacted at room temperature with four different impact energies ranging from 25 to 40J.

2.2. Drop tower impact testing

The reference results refers to impact tests conducted on the same composite material by means of a drop tower as described in details in [3]. These tests were performed using a drop tower system with a 16 mm diameter, 2 kg impactor, complying with the requirements of the Airbus Industries Test Method (AITM 1-0010). Just before impacting the specimen, an optical laser measures the impact velocity. A piezoelectric force sensor is placed inside the impactor to measure contact force during impact. The rectangular specimen whose dimensions are 100 × 150 mm^2 is simply supported on a frame (Fig. 2).

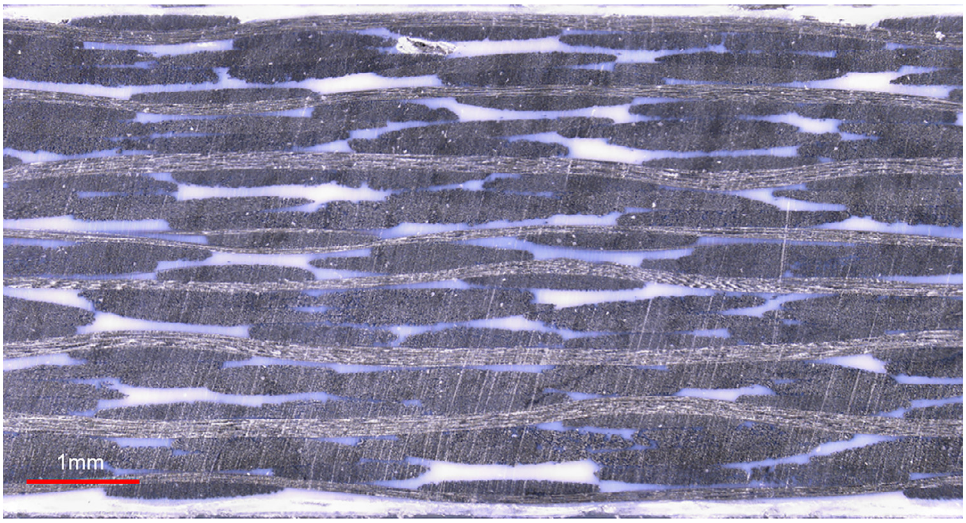

Fig. 1. Optical micrograph of the longitudinal section showing the quasi-isotropic stacking sequence of the C/G/PEEK laminates.

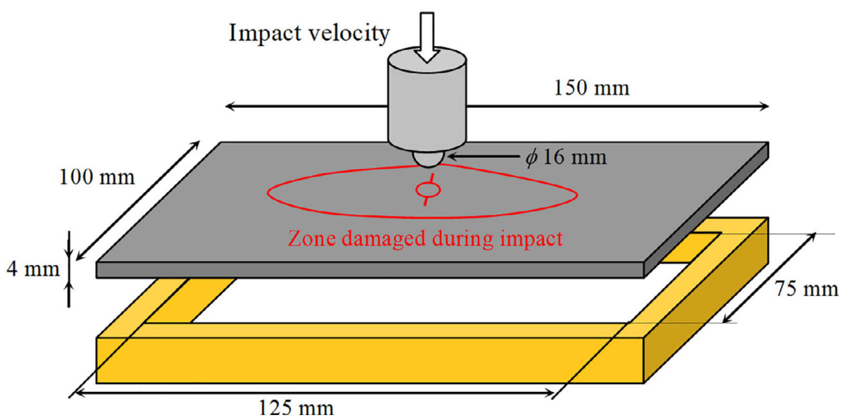

Fig. 2. Dimensions of the supporting frame used for drop-tower and Charpy impact testing [3].

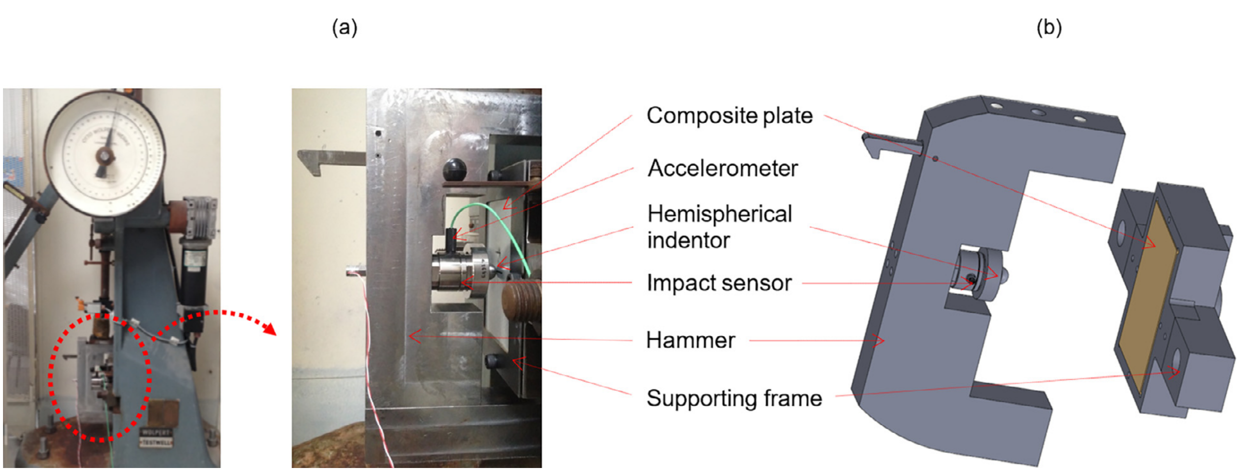

Fig. 3. Low velocity impact testing: (a) Charpy pendulum and measurement devices – (b) Parts design.

2.3. Charpy impact testing

The present testing device relates to impact testing machines, wherein the specimen meets the requirements of the Airbus Industries Test Method (AITM 1-0010). Specimens are impacted by a swinging pendulum hammer equipped with a hemispherical indentor (Fig. 3). This testing device is an improvement in the Charpy pendulum initial design. The specimens are usually V-notched rectangular beams designed to be striked at the center. A purpose of the device is to produce a pendulum for an impact testing machine in which no portion of the pendulum is located below the striking surface, so that the problem of interference is greatly reduced or even totally eliminated. This requirement must also be satisfied in order to meet the standard specifications of the American Society for Testing Materials for pendulum-type impact testing machines (ASTM Specification E-23).

In typical Charpy pendulum-type impact testing machines, the above requirement relating to the center of percussion has usually been met by constructing the pendulum in the shape of a long thin stem, at the

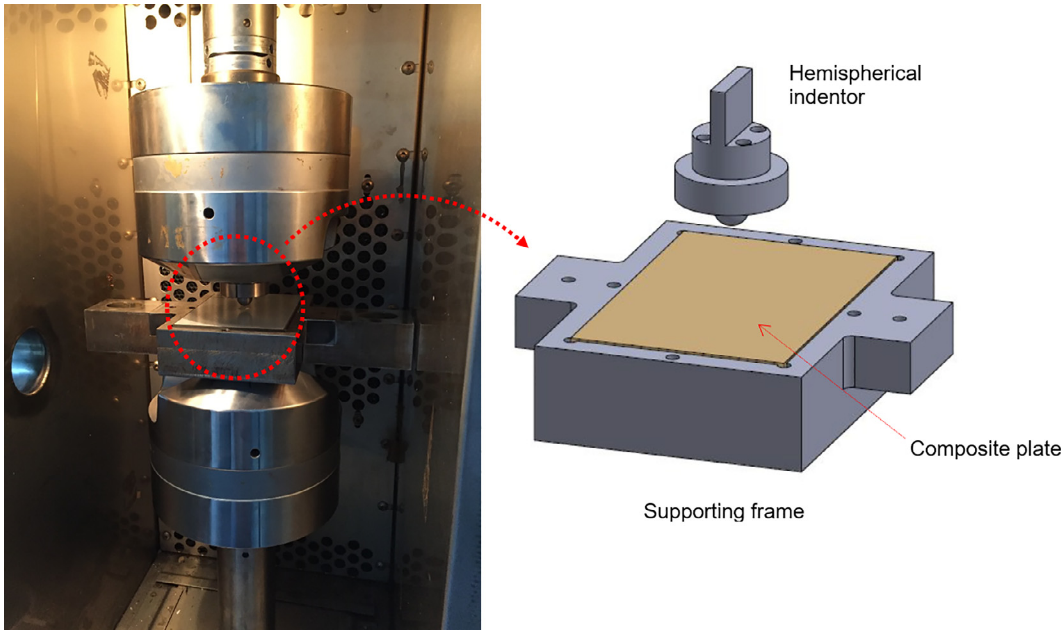

Fig. 4. Experimental set-up of the quasi-static indentation tests.

lower end of which a heavy head is attached, the head containing the striking surface. Most of the mass of the pendulum is thus concentrated in the head. One disadvantage in such a pendulum is that a considerable portion of the pendulum head must be located below the striking surface in order to place the center of percussion of the pendulum exactly at the center of the striking edge [5]. This often produces serious problems of interference, since the two parts of the broken specimen, being projected out after the moment of impact, may hit the lower part of the head, thus changing the energy relations and producing an erroneous test result. Following the idea initially proposed by Meola et al. [18,19], the impact tests performed in the present work are mainly intended to produce Visible Impact Damage (VID) or Barely Visible Impact Damage (BVID) on laminated plates supported by a standardized supporting frame (AITM 1-0010), rather than a complete fracture of a specimen (Fig. 2). The impact velocity is estimated from the fundamental principle of dynamics. In order to investigate the impact behaviour of C/G/PEEK laminates, four impact energies (25-30-35-40J) have been considered to ease the comparison with the results obtained from impacts achieved using the drop tower [3].

2.4. Quasi-static indentation tests

All the quasi-static indentation tests were performed using a 100kN capacity load cell of a MTS 810 servo-hydraulic testing machine in displacement-controlled mode (Fig. 4). These tests are conducted with the same supporting frame, as well as the same hemispherical indentor. The applied displacement loading rate is 1 mm/min ($1.67.10^{-5}$ m/s).

2.5. Permanent indentation measurement

The measurement of the specimen's permanent indentation is typically used to assess the severity of impact damage. In general, the indentation just after the impact (temporary indentation), is always higher than the indentation after relaxation of the impacted composite. Such relaxation effects are neglected after 48h to get the permanent indentation [20]. According to AITM 1-0010 Airbus standard, the BVID (Barely Visible Impact Damage) is defined by 0.6 mm of indentation after relaxation of the structure and without being exposed to any humidity [21]. The permanent indentation is measured using a 3D Keyence optical microscope (Fig. 5).

3. Results and discussion

3.1. Influence of impact energy on Charpy impact response

Low velocity impacts are classically conducted at different impact energies in order to evaluate the capability of the composite material to dissipate the impact energy (Fig. 6a). Impact energy is usually dissipated by different mechanisms including damage and local plastic deformations of the polymer matrix. When subjected to low-velocity impacts, the elastic response observed on the force-displacement curve appears to be independent from the impact energy (Fig. 6b). The residual displacement increases with the impact energy. It is well correlated to the non-reversible phenomena (damage, plasticity). The oscillations observed on the force-displacement curves are associated with the natural modes of vibration of the impacting system (shaft, hammer, impact sensor).

Once the limit of the elastic behavior is reached (at about 7 kN), both damage and local plasticity contribute to the dissipation of impact energy. Not surprisingly, the dissipated energy increases along with the impact energy. Indeed higher impact energy leads to higher maximum displacement that comes along with more significant damage and plasticity within the laminates. The dissipated energy represents 50% of the initial impact energy at 25J, and 70% of the initial energy for a 40J impact. As far the typical impact variables are concerned (Table 3), the maximum impact force is virtually the same for all impact energies, whereas the impact velocity (about 2 m/s) and the permanent indentation increase by 30% and 60%, respectively. It is worth noticing that the permanent indentation is higher than the BVID (0.6 mm) for all the impact energies applied.

3.2. Influence of impact velocity on macroscopic impact response

Quasi-static (QS) indentation tests are performed to develop some preliminary understanding of impact damage characteristics in a much better controlled manner [22]. This knowledge of what to expect allowed the impact tests to be carried out more effectively. As pointed out previously, the quasi-static results are usually treated as very low velocity impacts (about 10^{-5} m/s) when examining the effect of impact velocity on damage at a later stage. Quasi-static indentation tests make it possible to examine the interaction of local indentation and global

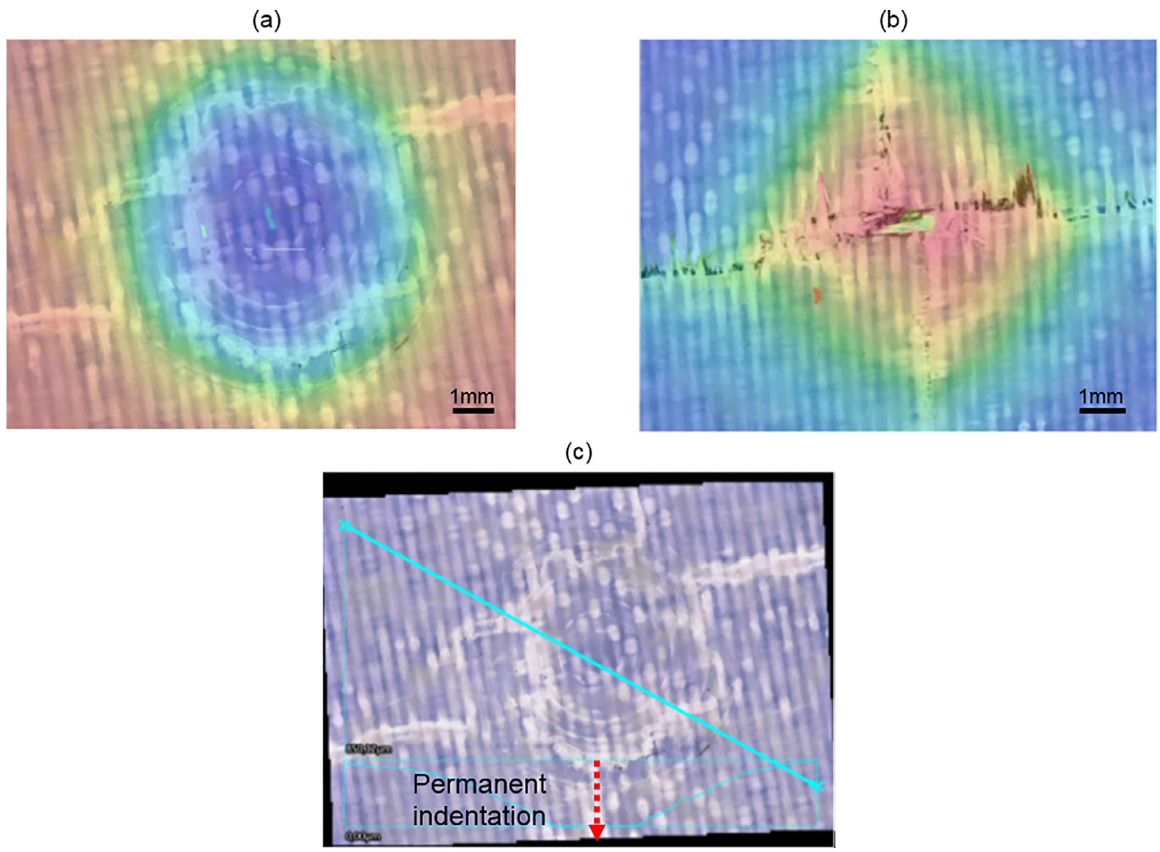

Fig. 5. Microscopic observations of the carbon-glass fibers reinforced PEEK composite laminates subjected to a 40J impact: (a) Impacted surface – (b) Rear surface – (c) Permanent indentation measurement from the indentation profile.

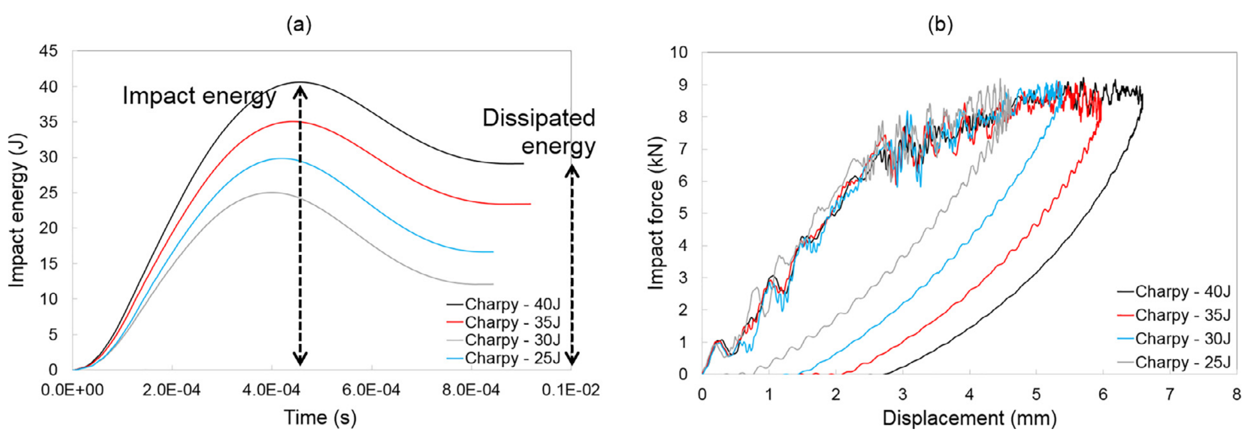

Fig. 6. Influence of impact energy on the impact response of carbon-glass fibers reinforced PEEK composite laminates: (a) Impact energy vs time – (b) Impact force vs displacement.

Table 3
Charpy pendulum impact testing: influence of impact energy on the mechanical response of carbon-glass fibers reinforced PEEK composite laminates.

Impact energy (J)	Maximum impact force (kN)	Time to peak force (s)	Maximum displacement (mm)	Energy dissipated during impact (J)	Normalized dissipated energy (% of impact energy)	Impact velocity (m/s)	Permanent indentation (mm)
25	9.42	$3.96.10^{-3}$	5.24	12.0	48 %	1.96	0.66
29.9	9.60	$4.09.10^{-3}$	5.33	17.65	59 %	2.14	0.83
35.1	9.63	$4.40.10^{-3}$	6.28	22.7	65 %	2.32	0.92
40.6	9.86	$4.54.10^{-3}$	6.56	28.8	71 %	2.50	1.07

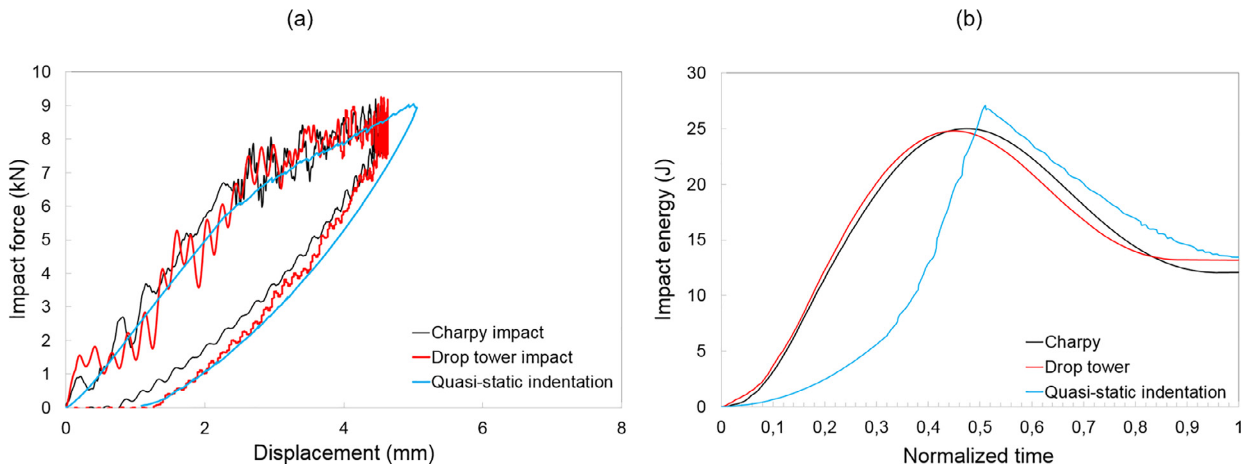

Fig. 7. Influence of loading conditions on the impact response of carbon-glass fibers reinforced PEEK composite laminates subjected to a 25J impact: (a) Impact force vs displacement – (b) Impact energy vs time.

Table 4
Drop tower impact testing: influence of impact energy on the mechanical response of carbon-glass fibers reinforced PEEK composite laminates.

Impact energy (J)	Maximum impact force (kN)	Time to peak force (s)	Maximum displacement (mm)	Energy dissipated during impact (J)	Normalized dissipated energy (% of impact energy)	Impact velocity (m/s)	Permanent indentation (mm)
24.7	9.26	$1.59.10^{-3}$	4.61	13.0	53 %	4.88	0.36
29.4	9.44	$1.66.10^{-3}$	5.11	17.0	58 %	5.11	0.52
32.8	9.77	$1.68.10^{-3}$	5.58	17.8	54 %	5.62	0.58
39.7	10	$1.78.10^{-3}$	6.25	24.4	61 %	6.18	0.73

plate deflection and its effect on the onset of damage, which may be significant in thick laminates [23].

The loading rate in terms of applied displacement significantly differs depending on the impact method (QS, Charpy or drop tower impacts). It goes from $1.67.10^{-5}$ m/s (QS) to a few m/s for Charpy and drop tower impacts. The laminates mechanical response to QS indentation is characterized by a 25J mechanical energy. Regardless the impact velocity, it appears that QS, Charpy and drop tower impact tests have virtually the same impact macroscopic behaviour (Fig. 7a) and the same dissipated energy (Fig. 7b) for a 25J impact energy. In order to facilitate the comparison between the three loading conditions corresponding to the same mechanical energy (25J), time was normalized (Fig. 7b). In spite of time normalization, when comparing the QS indentation test and the impact tests, a significant offset appears on the curves representing impact energy vs normalized time. For the Charpy and drop tower tests the impact velocity varies from impact speed to zero (at maximum impact force), and then it becomes negative during the rebound of the indentor; whereas for the quasi-static test it has only 2 values +v0 and -v0. This explains the significant difference in Fig. 7b.

In this study, for a given mechanical energy (25J), the permanent indentation resulting from low-velocity impact tests is lower than the one resulting from quasi-static indentation test. The permanent indentation resulting from QS indentation is about 12% and 100% higher than the Charpy and drop tower impacts, respectively (Tables 3 and 4). This paramount difference should be discussed considering that impact velocity is 2.5 higher in drop tower testing with respect to Charpy testing for a 25J impact energy. This difference will be further investigated in the next section for different impact energies.

The macroscopic impact behaviours (force-displacement curves) are similar for all the impact energies investigated (Fig. 8). In addition, for a given impact energy, shock waves induced by impact velocity lead to oscillations of the impact force signal. Drop tower impacts are characterized by higher impact velocities (about 2-3 times as high as the ones resulting from Charpy pendulum). As a result, the oscillations are more noticeable on the curves of the impact tests conducted on the drop tower.

As far the typical impact variables are concerned (Table 3), the maximum impact force is virtually the same for all impact energies, whereas the impact velocity (about 2 m/s) and the permanent indentation increase by 30% and 60%, respectively. This result confirms that the impact velocity plays a significant role into the formation of the permanent indentation. This will be specifically discussed in the next section.

3.3. Influence of impact velocity on dissipated energy

The dissipated energy is about the same for low impact energies (e.g. 25 and 30J – Fig. 9c–9d) but is significantly higher (about 20%) in laminates impacted with the Charpy pendulum for higher impact energies (35-40J – Fig. 9a-9b). In drop tower impact testing, the dissipated energy represents 50% of the initial impact energy at 25J, and 70% of the initial energy for a 40J impact (Fig. 10a). In Charpy impact testing, the dissipated energy represents about 50% of the initial impact energy at 25J, and 60% of the initial energy for a 40J impact. It also appears that impact velocity being higher with drop tower testing; the impact duration at maximum impact force is shorter (Tables 3 and 4). With respect to drop tower impacts, the ratio of impact time at peak force of Charpy impacts is constant (about 2.5). This value is consistent with the ratio of the impact velocities. These results suggest that superior impact energies come along with local time-dependent damages that ultimately contribute to the formation of the permanent indentation.

The dissipated energy (about 60% of the initial impact energy) does not significantly depend on the impact velocity in the case of drop tower impacts as it increases by 17% for a 27% increase in the impact velocity (Fig. 10a). In the case of Charpy impact testing, it rapidly grows with impact velocity with 48% increase of the dissipated energy for the same increase in the impact velocity (Fig. 9a).

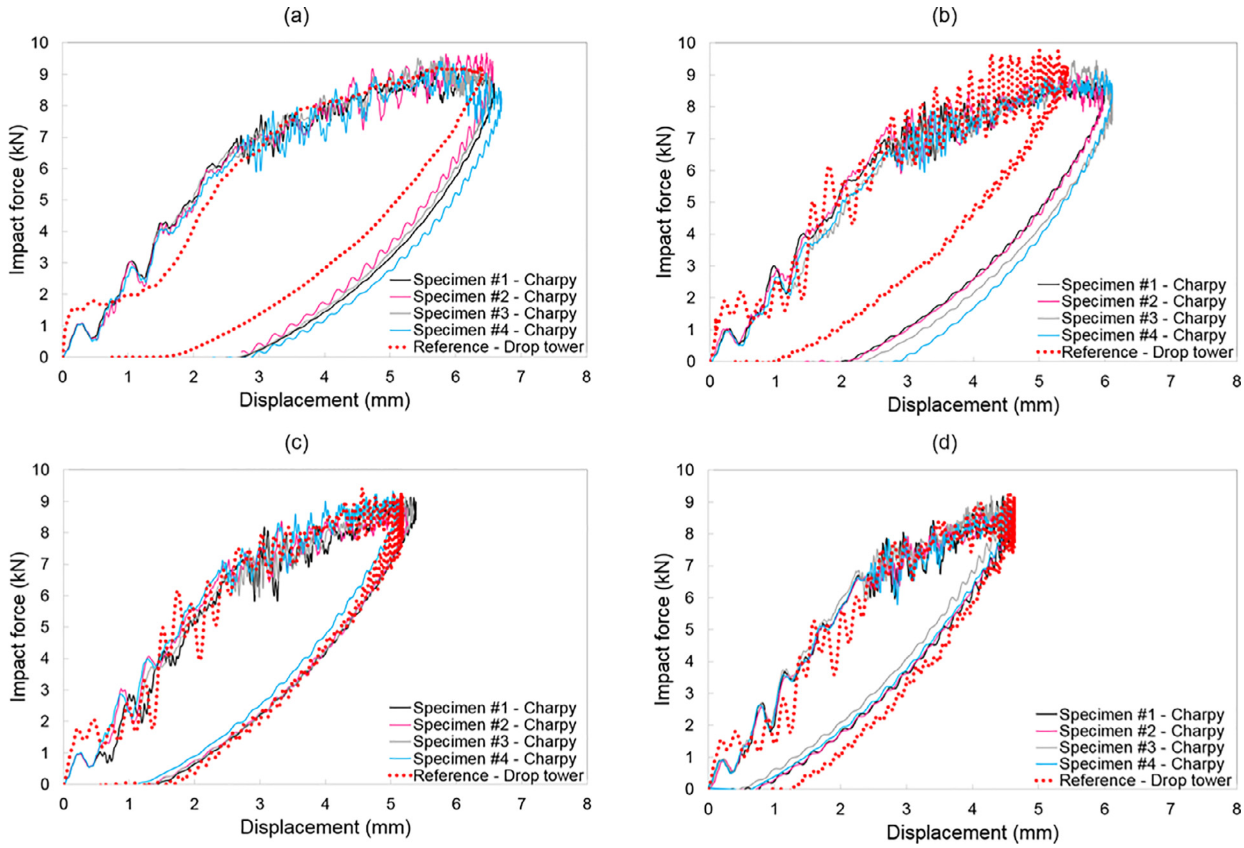

Fig. 8. Influence of loading conditions on the force - displacement response of carbon-glass fibers reinforced PEEK laminates depending on impact energy: (a) 40J – (b) 35J – (c) 30J – (d) 25J.

3.4. *Influence of impact velocity on permanent indentation*

The previous results suggest that impact velocity has no significant influence on the impact macroscopic behaviour, but it contributes to an increase in both the dissipated energy and the permanent indentation in proportions depending on testing method (Fig. 10b). The magnitude of permanent indentation is of the utmost importance regarding the residual mechanical properties of impacted laminates [24]. In the case of drop tower testing, a 27% increase in the impact velocity doubles the permanent indentation. In the case of Charpy testing, the same increase in impact velocity results in a 62% increase in the permanent indentation. It is also worth noticing that the permanent indentation is higher than the BVID (0.6 mm) for all the Charpy impact energies, and only in the 40J case with the drop tower.

With respect to QS tests, the permanent indentation is 10% and 50% lower for Charpy and drop tower impacts, respectively (for a 25J impact energy). Indeed, slow loading conditions are characterized by more permanent indentation. This result is consistent with the conclusions drawn in the literature [24–26]. For an impact velocity ratio of about 2.5 (drop tower over Charpy impact velocities), the permanent indentation is about 40% lower for a given impact energy. Thus, it appears that the permanent indentation is ruled by the impact velocity in thermoplastic-based laminates subjected to a given impact energy. It confirms that the time-dependent behavior of thermoplastic composites significantly contributes to the modification of their impact behaviour (from the permanent indentation standpoint) and their subsequent damage tolerance.

As already observed by Abdallah et al. in carbon reinforced epoxy-based laminates (whose mechanical behavior is usually less sensitive to loading rates than PEEK-based laminates), the damages induced by impact tests and quasi-static indentation tests are similar but the permanent indentation significantly differs depending on the impact velocity [25]. Previous section has highlighted the utmost importance of loading rate (or impact velocity) on the permanent indentation. More specifically, a slower impact velocity results in a larger permanent indentation. In the literature, this observation is explained by the difference in the chronology of damage mechanisms taking in place within the laminates subjected to slower or faster loading rates. The impact-induced damages are the same as the ones observed during drop tower impact tests [3], quasi-static indentation tests (very slow loading rate) and Charpy tests are characterized by debris resulting from local damage of the composite constitutive elements (broken fibers, delaminated plies, matrix cracking, fibers bridging). Compared to drop tower testing, this debris has a lot more time to move and to position itself in the delaminated areas and the different cracks. As a result, it prevents the cracks from reclosing as the impact decreases during the impactor rebound [25]. Ultimately, the mechanism of debris formation and the resulting blocking system are instrumental in creating a Barely Visible Impact Damage (permanent indentation). This non-reclosing of cracks is a very local phenomenon and ultimately has little effect on the macroscopic impact behaviour. As these are internal forces concentrated under the impactor, it really needs significant internal forces to have an observable effect on the external force, and thus on the force-displacement curves.

In hybrid carbon-glass reinforced PEEK laminates subjected to Charpy impacts, the microscopic observations classically show that the failure mechanisms are different on impacted and rear surfaces (Fig. 11). The impacted surface is characterized by a compressive failure of fibers. The impactor leads to a local hemispherical crushing. The rear surface shows a cross-shaped damage resulting from the breakage of 0° and 90° oriented fibers. The longitudinal and transverse cracks length increase as the impact energy increases. The presence of fibers bridging along the 0° and 90° is also typical of the role played by the glass fibers reinforced

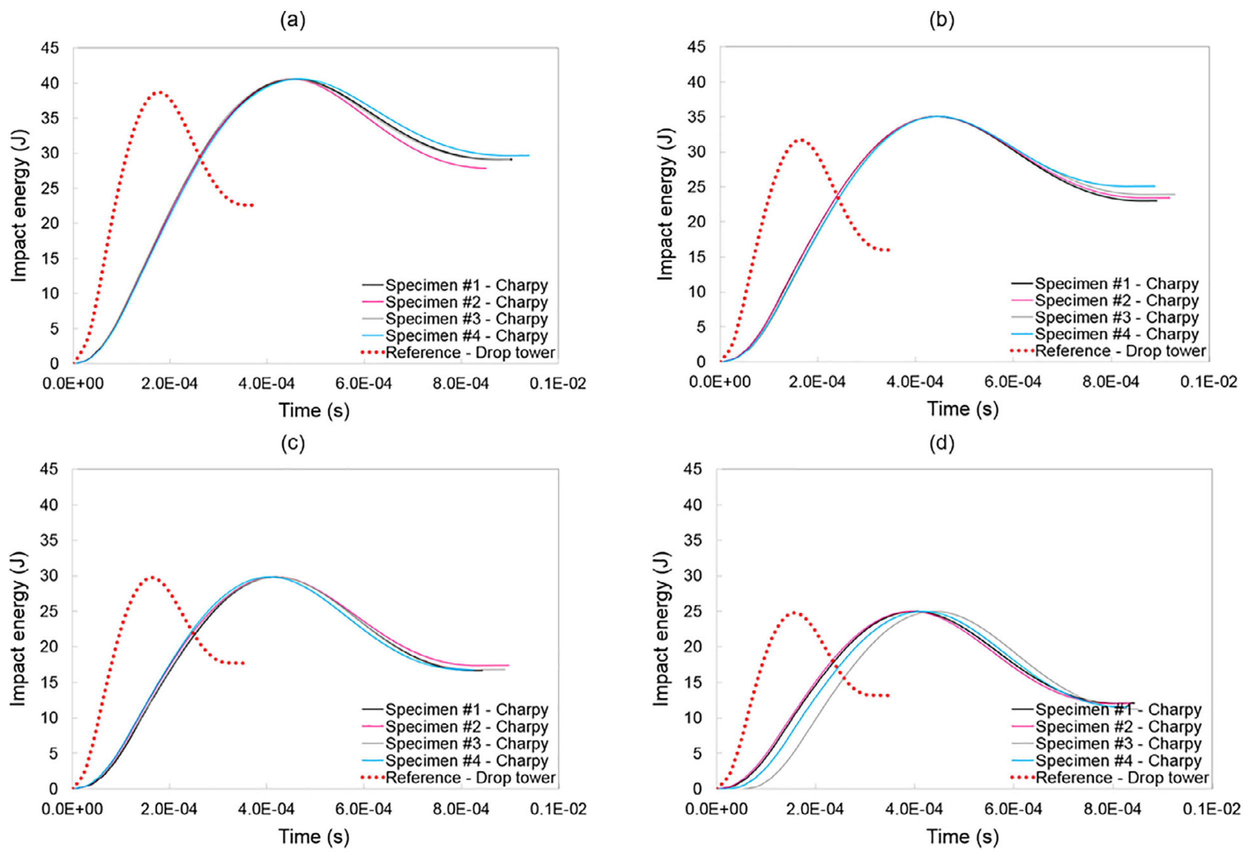

Fig. 9. Influence of loading conditions on the impact energy - time response of carbon-glass fibers reinforced PEEK laminates depending on impact energy: (a) 40J – (b) 35J – (c) 30J – (d) 25J.

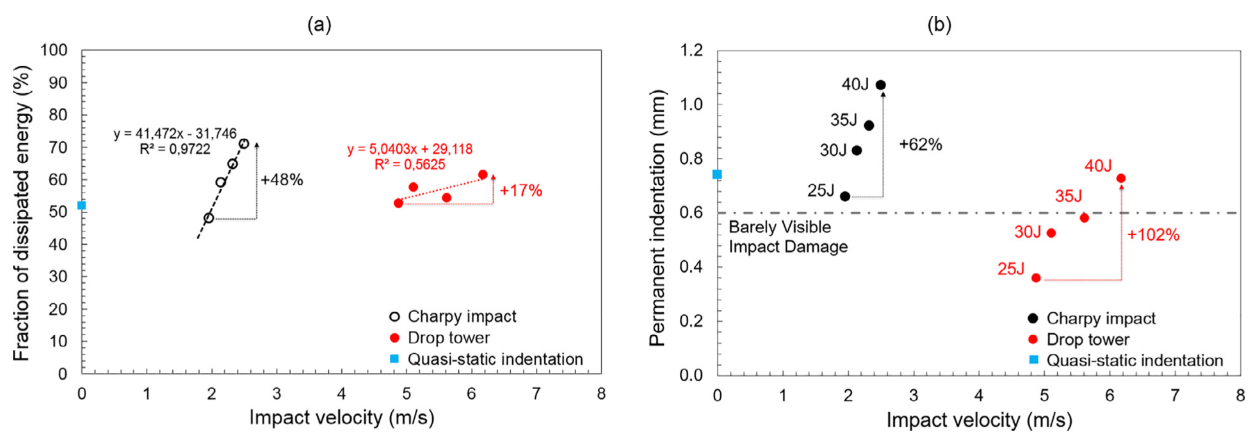

Fig. 10. Influence of loading rate (impact velocity) on the impact response of carbon-glass fibers reinforced PEEK composite laminates: (a) Dissipated energy vs impact velocity – (b) Permanent indentation vs impact velocity.

PEEK external ply in the toughness of the C/G/PEEK hybrid laminates. This glass fibers bridging is also instrumental in the reclosing of cracks as the elastic energy stored in the outer plies during impact loading is partially recovered during impact unloading. A longitudinal cut of the specimen subjected to Charpy impacts (40J) shows meta-delamination under the impacted surface as well as very localized matrix cracking and fiber breakage (Fig. 12).

In specimens subjected to drop tower impacts, impact-induced failure mechanisms were discussed in details in [3]. They are similar (meta-delamination, matrix cracking, fiber breakage) to the one observed in Charpy testing (Fig. 13). As indicated in the previous study, impacted-induced damages are very localized and limited through-the thickness. When comparing Charpy and drop towers impacts, the main difference is the significant delamination observed on at the vicinity of the rear surface.

4. Conclusions

The impact behavior of thick hybrid composite laminates consisting of a PEEK thermoplastic matrix reinforced by carbon and glass woven fabrics was addressed in this work. Different impact experimental methods (quasi-static indentation, Charpy and drop tower impacts) were investigated. These methods were based on the same hemispherical indentor but were characterized by different loading rates (or impact velocities). A Charpy pendulum was specifically adapted with the design of a

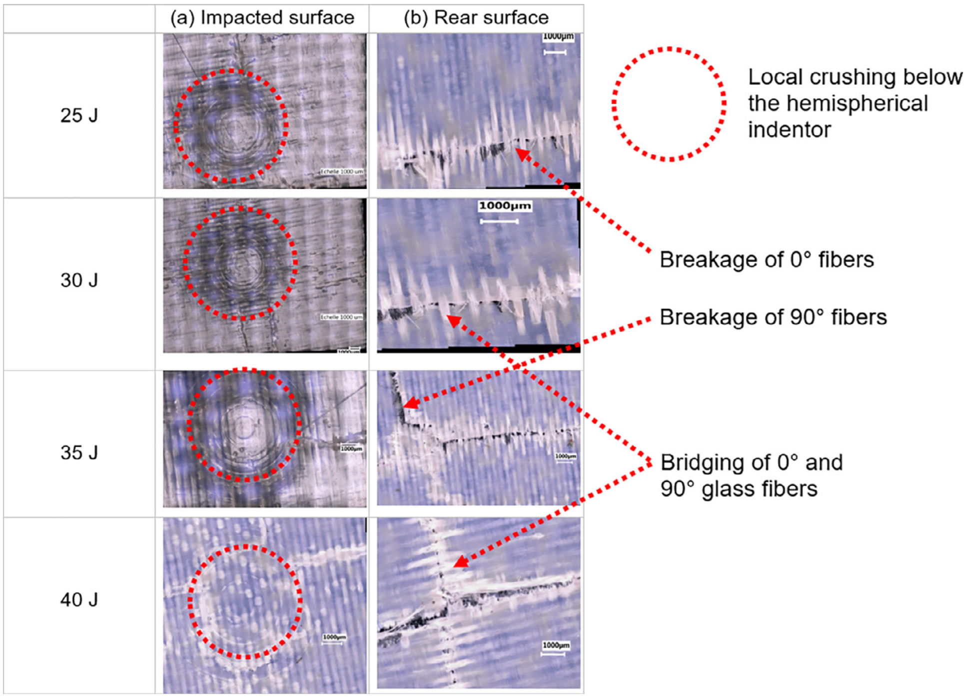

Fig. 11. Macroscopic observations of carbon-glass fibers reinforced PEEK composite laminates subjected to different impact energies: (a) Impacted surface – (b) Rear surface.

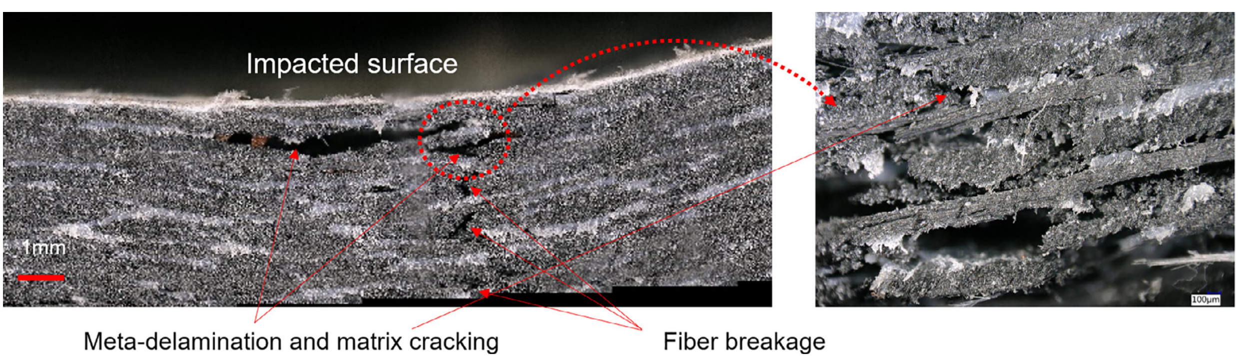

Fig. 12. Longitudinal cut of carbon-glass fibers reinforced PEEK composite laminates subjected to a Charpy pendulum 40J impact: observation of delamination under the impacted surface and breakage of 0° carbon fibers in consecutive plies.

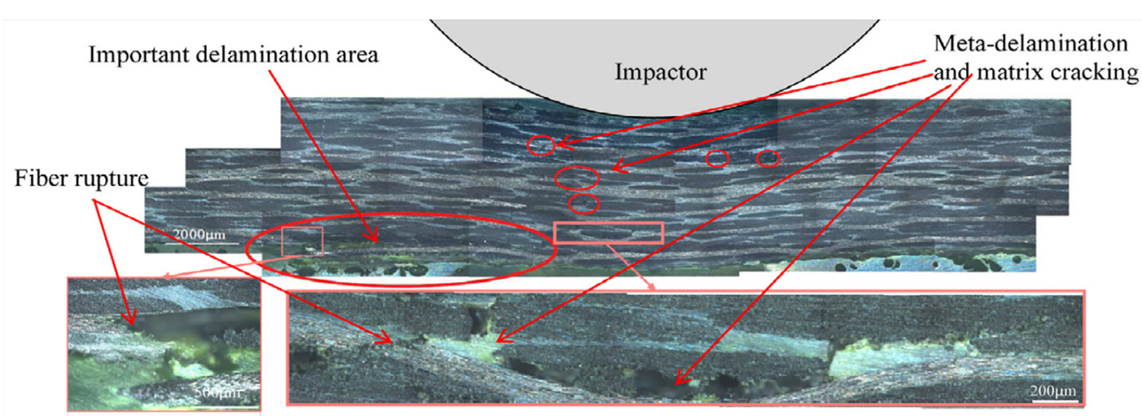

Fig. 13. Longitudinal cut of carbon-glass fibers reinforced PEEK composite laminates subjected to a drop tower 40J impact: observation of delamination under the impacted surface and breakage of 0° carbon fibers in consecutive plies [3].

hammer equipped with an instrumented hemispherical indentor and a supporting frame.

One of the main purposes of this study was to compare the influence of impact loading conditions and more specifically the impact velocity on the impact behavior of thermoplastic-based composite laminates that is usually quantified by the following characteristics: macroscopic mechanical response (force-displacement curve), total impact energy, dissipated energy and permanent indentation.

When applying a given impact energy, these impact methods led to similar impact behaviors in terms of force-displacement curves and dissipated energy. However, the resulting impact velocity significantly varied: a few 10^{-5} m/s in QS tests, about 2 m/s in Charpy tests and 5-6 m/s in drop tower tests. In addition, the permanent indentation associated with impact-induced damages significantly differed as it appeared to be ruled by the impact velocity. Higher impact velocities resulted in lower permanent indentation in drop tower impacts (about 40% lower than the Charpy impact values). At the same time, the impact velocity was 2.5 higher for drop tower impacts with respect to Charpy impacts for different impact energies.

The obtained results suggested that superior impact energies came along with local time-dependent damages that ultimately contributed to the formation of the permanent indentation. Quasi-static indentation tests (very slow loading rate) were characterized by debris, which were explained by the fact that the duration of quasi-static indentation tests were longer than the impact ones (Charpy and drop tower). As a result, the debris formed by impact-induced damages had more time to move and to position themselves in the delaminated areas and the different cracks. Ultimately, it prevented the cracks from reclosing as the impact force decreased during the impactor rebound. Charpy impact testing therefore led to permanent indentation values that were always higher than the Barely Visible Impact Damage (0.6 mm of permanent indentation) whose role is critical in laminated composites damage tolerance.

Finally, the instrumented Charpy pendulum is an alternative to horizontal impact devices to characterize the low-velocity impact behaviour of laminated composites as the severity of permanent indentation is greater. Further investigations are required to compare the CAI residual strength of laminates subjected to Charpy impacts with respect to drop tower impacts.

Declaration of Competing Interest

None.

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