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Influence of temperature on the impact behavior and damage tolerance of hybrid woven-ply thermoplastic laminates for aeronautical applications

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A B S T R A C T

Impact damage tolerance of hybrid carbon and glass fibers woven-ply reinforced PolyEther Ether Ketone (PEEK) thermoplastic (TP) laminates obtained by consolidation process is investigated. Service temperature being one of the most important parameters to screen TP or thermosetting matrix for aeronautical purposes, impact testing at room temperature (RT) and near the glass transition temperature (T_g) has been conducted. From the results, it turns out that temperature has little influence on the impact behavior in terms of maximum force developed or maximum deflection, though it reduces the dissipated energy especially at lower impact energy. However, temperature has a strong effect on the internal and external damages caused to the plate, as it increases the permanent indentation and it limits the projected delaminated area. As for the influence of temperature on the compressive residual strength of the laminates, it also appears that the classical experimental set-up for CAI tests is not completely appropriate to draw a clear cut conclusion. At last the obtained results show that the considered TP-based laminates are characterized by a very good impact behavior and a high-degree of damage tolerance.

Keywords:

Impact
Damage tolerance
Thermoplastic
High temperature

1. Introduction

Composite structures are very vulnerable to impact solicitation. Their strength can be harshly reduced without let a visible mark onto the surface. This mark left by the impactor on the impacted surface of the plate is known as the permanent indentation and is characteristic of the external damage caused by the impact. Requirements are based on the permanent indentation to define the acceptable loads for visibly and non-visibly damaged structures. The Barely Visible Impact Damage (BVID) is the arbitrary permanent indentation threshold value used as the minimum damage size detectable by visual inspection [1–3]. Lower than the BVID, the structure should withstand the ultimate loads when above the BVID the limit loads are required.

The use of carbon-fiber reinforced matrix composites has become a mainstay in aircraft production. Aircraft manufacturers are working to take benefit of thermoplastic (TP) materials which hold several key advantages over the thermoset (TS) type ones that are more commonly used, including damage tolerance, fire resistance or recyclability. Still, the high-temperature properties of

TP-based composites are usually lower than the TS-based ones, particularly when it comes to applying them in the surroundings of aircraft's engines. According to the TP material manufacturers, there is a wide range of TP materials now used in advanced composites components for the aerospace industry. Fabric reinforced TP composite materials are already used for many structural and semi-structural exterior as well as interior applications in existing Airbus programs (e.g. A380, A350). For high-temperature applications, PPS, PEI and PEEK polymers show many favorable characteristics for application in aerospace structures, but also offer excellent thermal stability – a critical property in a number of military, aero-engine and prospective supersonic business jet programs where aero-frictional heating can generate continuous service temperatures beyond the capabilities of high-temperature epoxy Ts (~180 °C).

1.1. About the impact behavior and damage tolerance of TP-based composites

The influence of matrix toughness on the impact behavior of carbon fibers reinforced TS (Epoxy) and TP (PPS and PEEK) laminates was first discussed in the late eighties [4]. Hsu et al. have observed similar impact-induced delamination damage areas in

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C/Epoxy and C/PPS laminates for a given impact energy. Through the comparison of impact damage behaviors of PEEK- and epoxy-based composites, Wang et al. have investigated the damage extension in C/PEEK cross-ply laminates under low velocity impacts [5]. From their results, it turns out that C/PEEK laminates are characterized by the same damage modes as epoxy composites. Depending on laminates' lay-up, matrix-controlled damage and fiber-controlled penetration are both identified as being the primary failure modes. In order to examine the combined influence of reinforcement architecture (e.g. woven-ply laminates) and matrix toughness, Ghasemi Nejjhad et al. have studied the impact behavior of carbon fiber fabrics reinforced PEEK and PPS composite systems [6]. Performing impact tests at room temperature, they concluded that the effect of the impact velocity on the impact performances is not significant. However the impact energy significantly influences the impact performance of the laminates. On the one hand, C/PPS laminates display high resistance to perforation as they are prone to extensive delamination. On the other hand, C/PEEK laminates demonstrate an ability to confine impact-induced delamination area, hence resulting in a high degree of damage tolerance.

More recently, through the comparison of the low velocity impact behavior of carbon fibers woven-ply laminates consisting of different matrix systems (Epoxy-PPS-PEEK), it was observed that C/Epoxy laminates experience larger delamination than TP-based laminates [7]. From the conclusions drawn in this study, it appears that composites with a tough TP matrix system experience reduced damage, what contributes to provide them higher impact-performances. In these woven-ply laminates, the prominent role of the satin weave fabrics is also emphasized as it limits extensive delamination. In addition, it is also observed that fiber-bridging is instrumental in reducing the extension of inter-laminar and intra-laminar cracks, as well as delamination. In the sequel of the previous study, the residual compressive strength and behavior of TS-based (epoxy) and TP-based (PPS or PEEK) laminates initially subjected to low velocity impacts have been compared [8]. From the conclusions drawn, permanent indentation appears to be of the utmost importance to promote local buckling in impacted laminates subjected to compressive loadings. Unexpectedly, compression after impact tests suggest that matrix toughness is not the primary factor governing damage tolerance. However, matrix ductility contributes to ease local plastic micro-buckling at the crimps (where weft fiber bundles undulate over warp fibers in weave fabrics), therefore slowing down the propagation of transverse cracks.

1.2. Influence of temperature on impact behavior and damage tolerance of reinforced PMCs

As matrix ductility and toughness of matrix are enhanced at high temperature, many authors have investigated the influence of temperature on the impact behavior and damage tolerance of fiber-reinforced PMCs (Polymer Matrix Composites). Most of the studies available in the literature are related to glass fibers [9–12] or carbon fibers [13–18], and more recently the effect of reinforcement hybridization on the low velocity impact behavior has been evaluated in hemp-basalt [19] or Kevlar/glass reinforced composites [20]. Many references deal with epoxy-based composites [9–15], but very few with TP-based laminates [16–18]. Through the comparison of C/Epoxy and C/PEEK laminates, Im et al. have studied the effects of extreme temperature variations on impact damage of orthotropic laminates [16]. They observed that the impact-induced delamination areas decrease as the temperature increases. In PEEK-based laminates, the frequency of transverse cracks is reduced. Bibo et al. have also investigated the influence of matrix type and morphology on the ability of the composite to withstand penetration, absorb energy and sustain

damage at different temperature levels (RT, 80 °C and 150 °C). At high energy, full penetration of the specimen takes place by the indenter. At low energy, impact damage is induced but the plate is not ruptured. They concluded that test temperature has little influence on through-penetration impact results, although high-temperature testing does increase the spread of delamination in epoxy-based laminates subjected to low-energy impacts [17,18]. In addition, the effect of impact-induced damage on high-temperature residual compressive properties has been investigated. An increase in the testing temperature has a significant effect on the post-impact compression strength, whereas the impact temperature has a marginal effect. There is evidence that the growth of impact generated delamination is restricted at the high temperatures during compression compared to growth at room temperature in the case of the TS toughened epoxy, but this is not the case for the PAS (PolyAryl Sulfone) TP. On the contrary, at low temperatures (e.g. –25 and –50 °C), Russo et al. have studied the low velocity impact behavior of TP laminated structures based on TP polyurethane reinforced with woven glass fibers [21]. In order to verify the potential applications of these materials, they concluded that low temperature impacts result in an increased stiffness of tested specimens and a higher propensity to damage. They also observed no impact-induced delamination at low temperatures. Increases of plate thickness and decreases in the test temperature lead to enhanced friction phenomena at the material-dart contact. Ultimately, TP can be considered to replace conventional brittle TS matrix for applications under severe environmental conditions. More recently, Sorrentino et al. have studied the effect of temperature on static and low velocity impact properties of polyethylene-naphthalate (PEN) thermoplastic composites [22]. By means of quasi-static flexural and low velocity impact tests, they evaluated the structural response of carbon fibers plain weave fabrics reinforced PEN laminates at different temperatures (20, 60 and 100 °C). Considering that the glass transition temperature of the material is about 120 °C, they observed a reduced influence of temperature (even at 100 °C) on the flexural stiffness, but a low impact resistance. However, it appears that C/PEN/laminates are characterized by an increase in their impact performance as temperature increases. They assumed that temperature contributes to the enhancement of the TP matrix toughness and a higher strength of the fiber/matrix interface, ultimately explaining this phenomenon.

1.3. Objective of the study

This study deals with impact behavior and damage tolerance of a laminated composite consisting of 14 carbon-PEEK 5HS (Harness Satin) woven plies with two outer glass-PEEK woven plies (Table 1) whose aim is to protect the carbon core (electrical protection). The effect of temperature on impact-induced damages and the residual compressive behavior of the laminates are investigated. A Dynamic Mechanical Thermal Analysis (DMTA) analysis showed that the glass transition temperature (T_g) of the studied material is about 145 °C. Several impacts at different level of energy are carried out at room temperature (RT) and at 150 °C (i.e. slightly higher than T_g). Investigations are focused on the delamination surface,

Table 1
Mechanical properties of C/PEEK and G/PEEK woven-ply laminate at RT.

	Carbon fibers/PEEK	Glass fibers/PEEK
E_1 (GPa)	60	22
E_2 (GPa)	60	20
G_{12} (GPa)	4.2	4.0
Nominal ply thickness (mm)	0.31	0.25
T_g (°C)	145	145

the permanent indentation and the dissipated energy. In order to evaluate the damage tolerance, Compression After Impact (CAI) tests are performed. CAI tests have been conducted at RT. Altogether, twenty specimens ($150 \times 100 \text{ mm}^2$) were impacted at two temperatures (RT or $150 \text{ }^\circ\text{C}$), and sixteen specimens were subjected to compressive loading after impact at RT. Both impact tests and CAI tests were carried out in agreement with the Airbus Industries Test Method (AITM 1-0010).

2. Experimental study and specimen configurations

Nine samples were impacted at room temperature (referred to as the RT series) and ten at $150 \text{ }^\circ\text{C}$ (Tg series), all of them having the same layout configuration. The laminated plates are made up of carbon (Tenax[®]-E HTA40 3K)-PEEK 5HS woven plies with a glass-PEEK ply on each surface and obtained by thermostamping process (Table 1). The stacking sequence, consisting of 14 carbon-PEEK and two outer glass-PEEK woven plies, is balanced and symmetric and the thickness of each laminate is about 4.5 mm: $[(0/90)_G, [(0/90), (\pm 45)]_3, (0/90)]_s$ (with G index for glass fibers ply)

Impact 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 velocity of impact. A piezoelectric force sensor is placed inside the impactor to measure contact force during impact. The rectangular specimen measures $100 \times 150 \text{ mm}^2$ and is simply supported on a $75 \times 125 \text{ mm}^2$ frame. The impact setup is shown in Fig. 1a. For the impacts at $150 \text{ }^\circ\text{C}$, the plates were heated up to the desired temperature using a hot-air oven prior to impact. For both temperatures, the impact energy ranged from 20 J to 40 J by increments of 5 J.

CAI tests were then performed on a hydraulic testing machine. The specimen being stabilized by a $90 \times 130 \text{ mm}^2$ window formed by anti-buckling knife-edges and clamping blocks (Fig. 1b), in agreement with the previous test method. During the test, digital image correlation (DIC) enabled to follow strains and displacements of the impacted face (painted with a random speckle pattern) whilst extensometer and LVDT captor recorded respectively local strain and out-of-plane displacement on the non-impacted face (Fig. 2). Out of the nineteen impacted plates, seven from RT impact tests and eight from Tg impact tests were tested in CAI, the remaining four being kept for microscopic observations of the internal damages. A non-impacted plate (referred to as virgin in the paper) was also tested in compression for reference purposes.

3. Results

The experimental results are presented in two parts. The first sub-section deals with the impact results and the damages engendered by the impact while the second sub-section deals with the results of CAI.

3.1. Experimental results from impact tests

3.1.1. Impact behavior

Laminates response to impact is generally presented as a force-displacement curve and an energy-time curve, as shown in Fig. 3 for a 30 J and a 40 J impact at $20 \text{ }^\circ\text{C}$ (RT) and $150 \text{ }^\circ\text{C}$ (Tg). As expected, the displacement is more significant as the impact energy is higher. A little difference is observed between impacts at RT and $150 \text{ }^\circ\text{C}$. The experiments at $150 \text{ }^\circ\text{C}$ show a slightly lower impact force and a higher damping. At high temperature, the lower

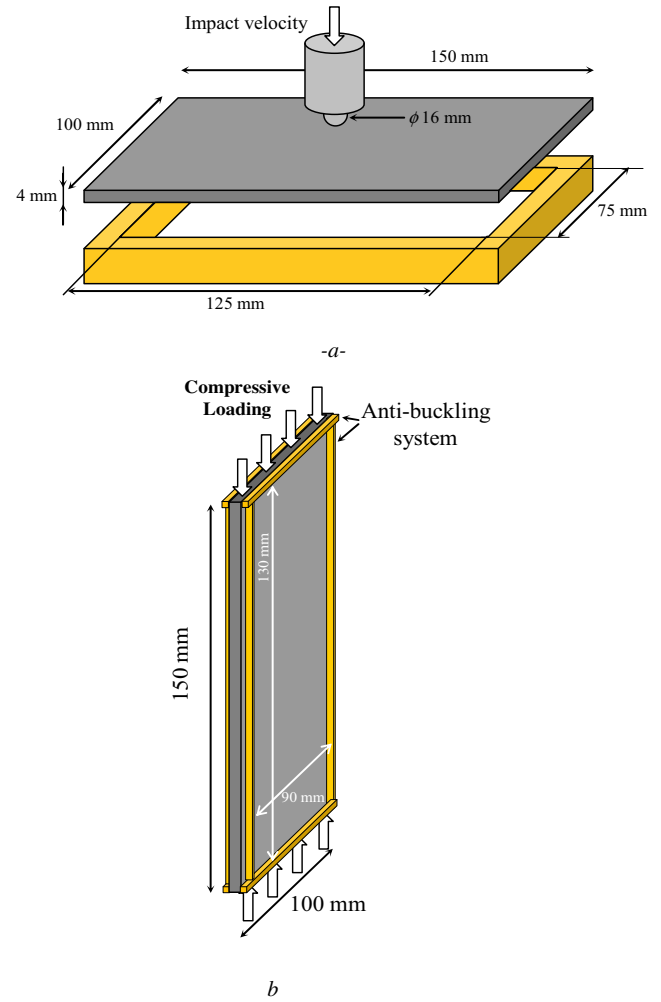


Fig. 1. Test setups for impact (a) and CAI (b).

impact force might be explained by lower out-of-plane shear modulus [7], and higher damping capacity due to the increase in viscosity of PEEK matrix with increasing temperature [23,24].

Fig. 4 presents the impact response data – namely maximum force (-a-) and maximum plate deflection (-b-) during impact – for each test with respect to the actual impact energy. The series of impacts at RT and above Tg are highlighted to investigate the effect of temperature. Firstly, it appears that maximum force is virtually independent of impact energy (of course it is true for the chosen impact energies but not for very low energy) and is slightly lower at Tg. The decreasing of the out-of-plane shear modulus with temperature should explain this little difference. Secondly, maximum plate deflection is linear to the impact energy and there seems to be no clear difference between the RT and Tg series in impact behavior, even if the displacement at high temperature seems to be higher, as expected.

In Fig. 5, the normalized dissipated energy during impact – ratio of the area within the force-displacement curve and the total impact energy – is plotted vs the impact energy. The observed trend is an increasing dissipated energy as the impact energy increases for both temperatures. Indeed, higher impact energy results in more damages and so higher dissipated energy. This mechanism is well known at room temperature [3]. In general more energy is dissipated during the impacts at $20 \text{ }^\circ\text{C}$ but this is mostly the case for the lowest impact energies, whereas the dissi-

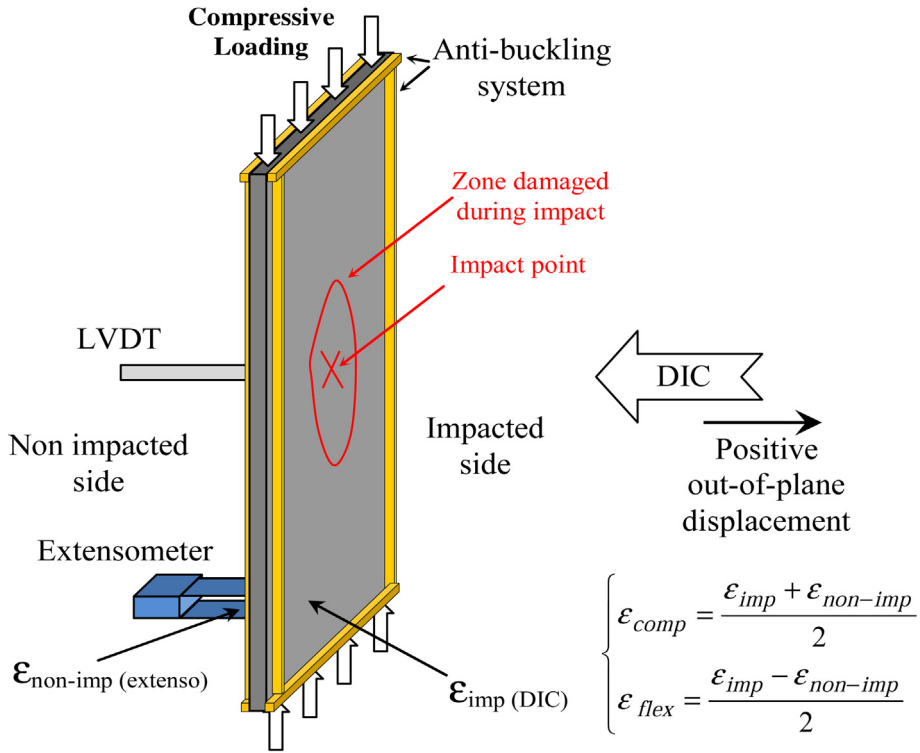
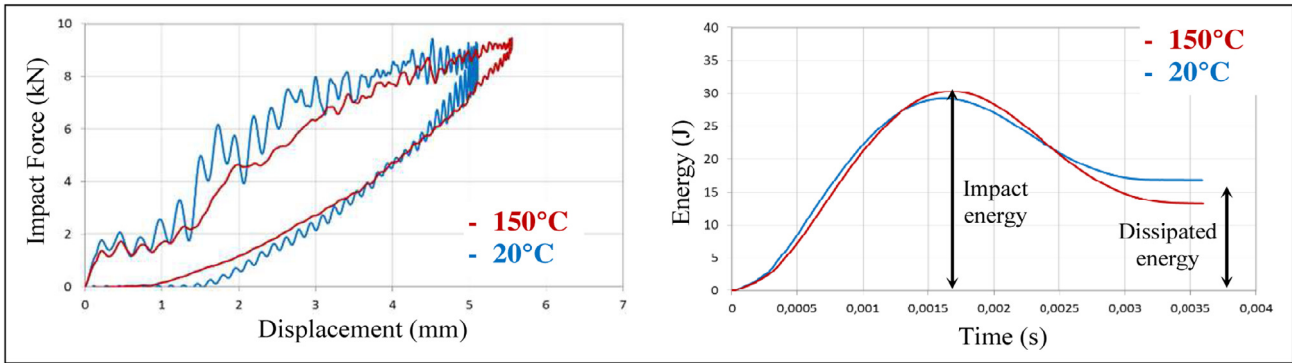
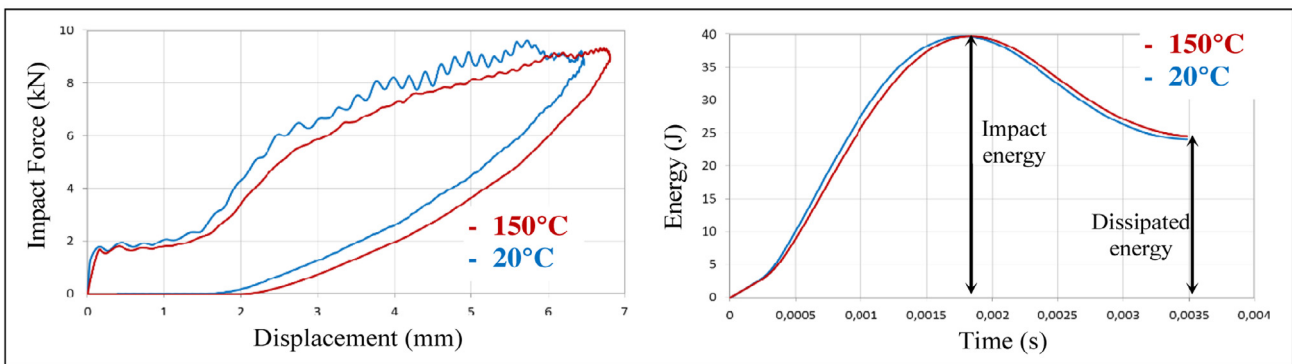


Fig. 2. Measuring instruments settings during CAI.

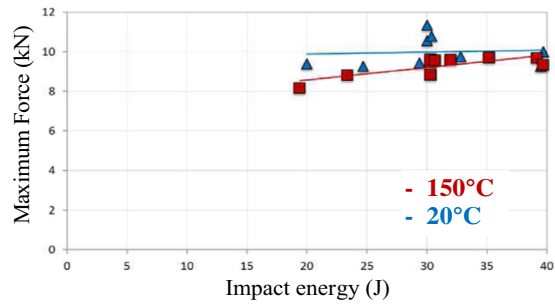


a

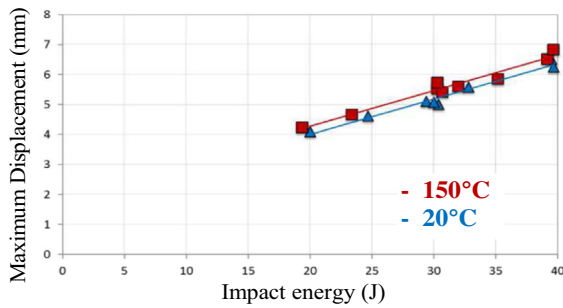


b

Fig. 3. Force-displacement and energy-time curves of the impact at -a- 30J and -b- 40J.



a



b

Fig. 4. Summary of the specimens' impact response with respect to impact energy.

pated energy is the same ($\approx 60\%$) for the four 40 J impacts at 20 °C and 150 °C.

3.1.2. Permanent indentation

The permanent indentation let by the impactor after impact event is considered as the dent on the surface of the plate. It is defined as the difference in a direction normal to the face of the specimen between the lowest point in the dent and the surface that is undisturbed by the dent [25]. Because of the dependence of this phenomenon on several parameters (plate geometry, material, boundary condition, stacking sequence...), its origin is not well controlled yet... Whatsoever it is probably driven by the ductile and associated non-linear shear behavior of the matrix [26,27], matrix cracking and blocking debris [28] and local fiber failure

[29–31]. It is precisely measured using a DIC technique. For this study, the BVID is taken at 0.5 mm of dent depth [1–3]. The value of the permanent indentation for each test can be found in Fig. 6 with respect to the impact energy. It was measured 48 h after impact to account for the natural elastic relaxation of the material. What one can see is a very clear temperature effect in this case, over the entire impact energy range, where the permanent indentation is higher for the impact at Tg by a 1.2–1.5 factor. Consequently, if one considers the energy at BVID, it has dropped by 24% from 29 J at 20 °C to 22 J at 150 °C. This result is very interesting because it shows the positive effect of the temperature on the permanent indentation. Then the impact damage tolerance, which is directly linked to the impact damage detectability, will be improved at high temperature.

3.1.3. Delamination

From the impact-induced damage standpoint, delamination is inspected using a non-destructive ultra-sonic C-Scan technique. A typical C-Scan is shown in Fig. 7 for a 40 J impact at RT and Tg. To be noted: specimen (a) is then cut and microscopically observed here after (Fig. 9). Firstly, impact at RT exhibits larger projected area of delamination, this observation is confirmed in Fig. 8 which represents the delaminated area versus impact energy from every impacted sample and suggests a few remarks.

To begin with, the projected delaminated area increases with impact energy at both RT and Tg, as expected. Also, compared to the delamination occurring in unidirectional Ts composites [31], the delaminated area remains fairly small at 20 °C, less than 600 mm² as shown in Fig. 8, even for high impact energies. For example, to author's knowledge [31], for several stacking sequences with T700/M21 unidirectional carbon/epoxy, the delaminated area is higher than 1200 mm² for 25 J impact at RT with equivalent thickness and impact boundary conditions. The comparative study of woven-ply carbon fiber-reinforced TP and TS composites subjected to impact led by Vieille et al. [7] draws to the same conclusion about delaminated area extension: TS composites are more prone to delamination than TP when subjected to low velocity impacts.

Then, similarly to the external damage, the impact temperature has a tremendous influence on the internal damage i.e. delamination. If we consider the trend curves, the delaminated area is divided by three over the whole range of impact energies. Consequently, delamination, on the whole fairly limited at 20 °C (at maximum the delaminated area covers only 4% of the total area), is very weak at 150 °C.

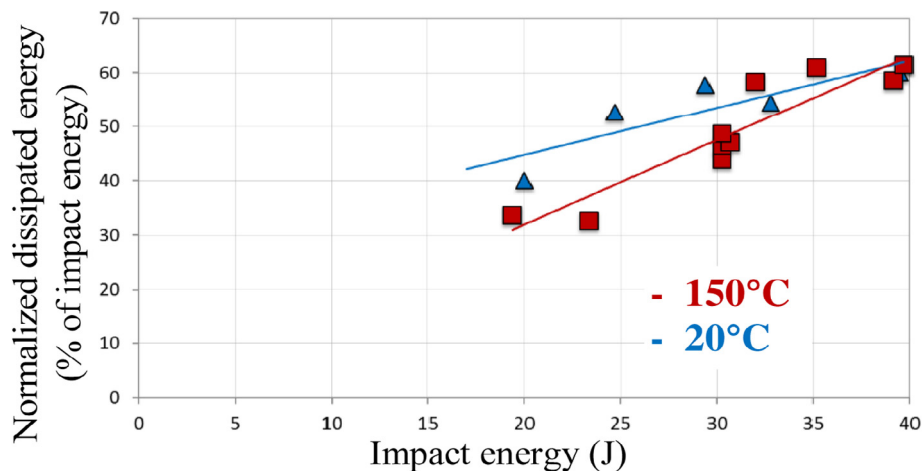


Fig. 5. Summary of the specimens' normalized dissipated energy.

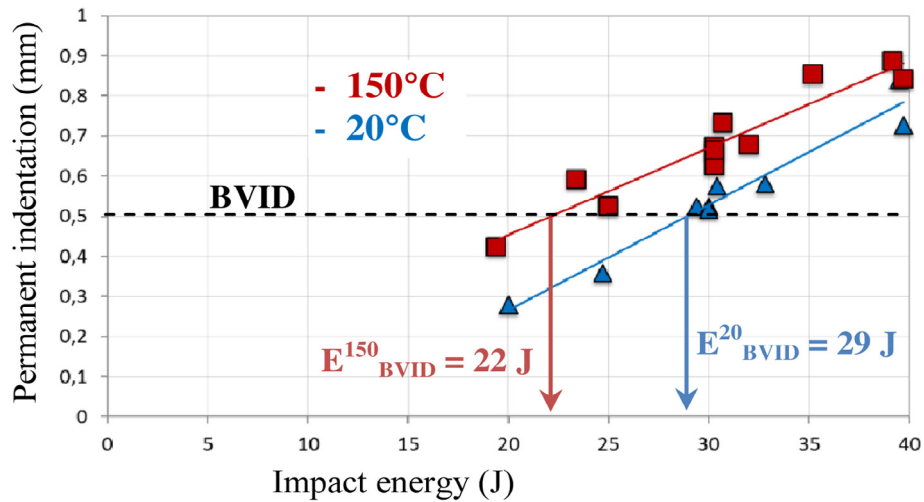


Fig. 6. BVID energy at 20 °C (RT) and 150 °C (Tg).

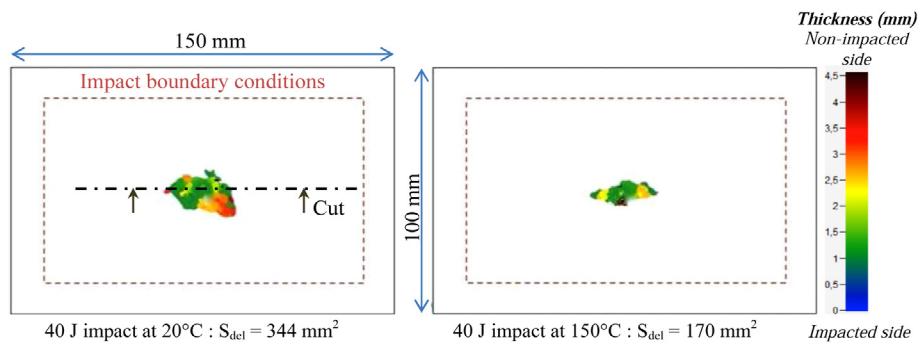


Fig. 7. C-Scan from impacted side of two specimens impacted at 40 J at 20 °C and 150 °C.

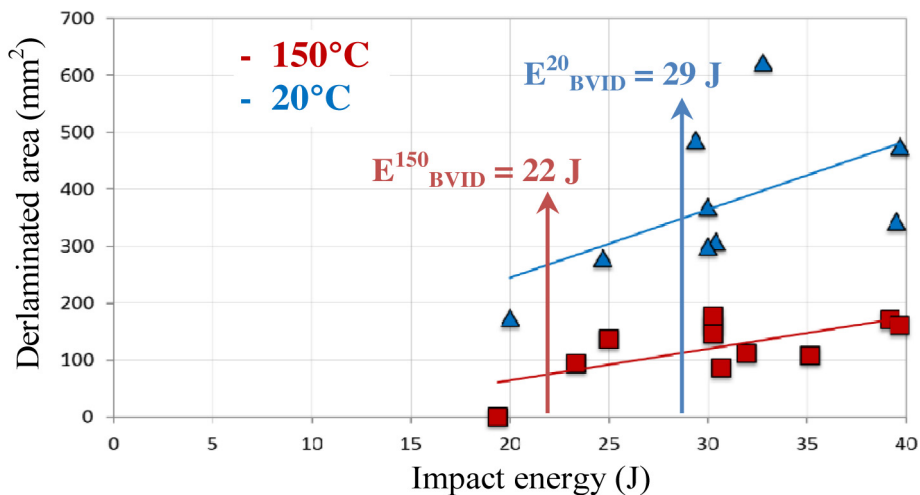


Fig. 8. Projected delaminated area versus impact energy.

Moreover, in order to design a composite using the impact damage tolerance, it is necessary to proof the structure can withstand the ultimate loads with an impact energy less or equal to the BVID energy [1–3]; then with a 29 J impact at RT and with a 22 J impact at 150 °C. Consequently, the impact damage will be very little, and especially for the RT test, because the delaminated area will be almost null. Of course a null delaminated area does not induce a

null damage, because other damage, such as matrix cracking, can be undetected using ultrasonic investigation. For example, for the 20 J impact at 150 °C, the delaminated area is null, but the permanent indentation is about 0.3 mm, which means impact induced damage.

In addition to the limited propagation of delamination due to the geometry of the woven plate [7], temperature also has a non-

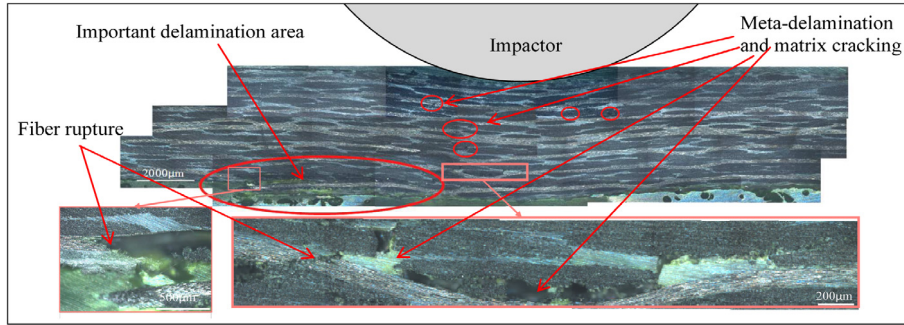


Fig. 9. Microscopic observations of the cross-section under the point of impact for a RT 40 J impact.

negligible effect. PEEK matrix being more ductile and tougher at high temperature, both properties lead to local plastic deformation before damage occurs, and consequently slows down matrix cracking and delamination.

Then microscopic observation of a sample's cut-face was performed (Fig. 9). Several samples were cut in half lengthwise right through the impact zone (see Fig. 7) where damage is most severe in order to observe delamination and fiber fracture. Fig. 9 shows the microscopic picture of a supposedly delamination-rich area of the plate's cut-face, previously impacted at RT and 40 J (delamination exposed Fig. 7a). It should be pointed out that the damage is scattered and quite limited, except on the non-impacted face with significant debonding. The occurrence of meta-delamination in the fabric i.e. delamination between the wrap and weft bundles [32], is present under the impactor, though it is quite difficult to observe.

3.2. Experimental results from CAI

In order to evaluate the compressive resistance after impact, fifteen impacted specimens and one non-impacted specimen were subjected to in-plane compressive loading on the CAI test fixture until failure. The typical output from CAI test are compressive stress-versus-strain curves as well as the plate's global buckling mechanism obtained from a LVDT sensor (Fig. 2) and digital image correlation technique. Three examples of CAI tests with different buckling directions are presented in Fig. 10.

In order to better understand the damage scenario developing during the CAI test, buckling modes were calculated for virgin specimens by a FE method (Fig. 11). For this FE calculation, a $90 \times 130 \text{ mm}^2$ rectangle was simply supported in order to simulate the experimental boundary conditions of CAI (Fig. 2a). It turns out that the first buckling mode to appear (Fig. 11) is the mode 2 buckling (2 blisters of opposite direction) at around -360 MPa and the mode 1 buckling (1 blister) appears shortly after at around -380 MPa (the mode 3 buckling appears much later at about -500 MPa). It can be noticed that we choose to denote mode 1 (2) the buckling mode with 1 (2) blister (s), even if it happens for higher stress loading. The proximity of these 2 buckling modes explains why, during the experiments, the two first buckling modes appears more or less at the same time depending on the boundary conditions which are not perfect during experiments, contrary to the FE simulation.

To analyze the obtained curves (Fig. 10), Z-displacement field of the three plates obtained by DIC technique is exposed Fig. 12.

The first one is the CAI test for a 35 J-impact at $150 \text{ }^\circ\text{C}$ (Figs. 10a, b and 11a). The local longitudinal strain from both sources, i.e. CCD cameras on the impacted side and extensometer on the non-impacted side, show the same tendency. The average of the longitudinal strain of both sides gives the compressive strain, whereas

the difference gives the flexural strain (Fig. 2). This example shows substantial flexural strain, which is corroborated by Fig. 10b (one has to pay attention to the scales of curves and images). The deflection is considered negative in the impact direction (Fig. 2b). The plate's deflection gradually increases in the direction of impact until failure, hence the negative values of flexural strain. In contrast, Fig. 10c and d show the opposite phenomenon, as the plate buckles in the opposite direction to that of impact. The positive values of the flexural strain confirm this observation. This behavior is somehow counter-intuitive. Given the residual deformation of the plate after impact as shown in Fig. 13, obtained by DIC, one would expect every plate impacted with a sufficient energy to buckle like 10-b during CAI. However, reverse buckling can occur when the impact energy is not high enough to induce sufficient damage within the material resulting in some decrease in its stiffness. According to the literature, this happens in about 15% of cases [33], but in this study the ratio was 25%. The very low degree of damage reported in Section 3.1 may explain this kind of buckling, and also may account for the higher reverse buckling ratio than the one usually observed.

Finally, the last CAI response is represented by the sample impacted at 31 J (real impact energy measured). The corresponding deflection curve (Fig. 10f) is characteristic of a sudden change in buckling mode. The initial out-of-plane displacement is mostly restricted at the location of the LVDT, but the DIC enables us to distinguish the out-of-plane displacement of the upper part of the specimen. Fig. 12c and d show this sudden modification of the plate just before failure, marked by point X1 and X2 in Fig. 10f. This plate exhibits a buckling starting in mode 1 and finishing in mode 2 (Fig. 11).

In order to compare the CAI results with other draping sequences or materials, it is useful to evaluate an equivalent failure strain. This equivalent failure strain is defined such as strain obtained at failure with linear strain-stress response. It avoids taking into account local non-linearity which are not representative of the global behavior of the structure. The first step is to evaluate the average compression stiffness. In this study, stiffness modulus is calculated from values of the stress and strain at about -150 MPa , taken from the linear part of the compression stress/strain curves (Fig. 10). The moduli featured some significant dispersion, ranging from 42.4 GPa to 50.4 GPa with an average of 46.5 GPa , the virgin specimen value being 48.7 GPa . For the sake of uniformity, the strain at failure is then computed for every specimen by dividing its respective failure stress by the averaged modulus. Consequently, these values of equivalent failure strain are consequently slightly smaller – in absolute value – than the obtained from compressive stress/strain curves, but are more representative of the global behavior of the structure.

For the purpose of evaluating the effect of damages on the residual strength of the material, CAI failure stress and equivalent

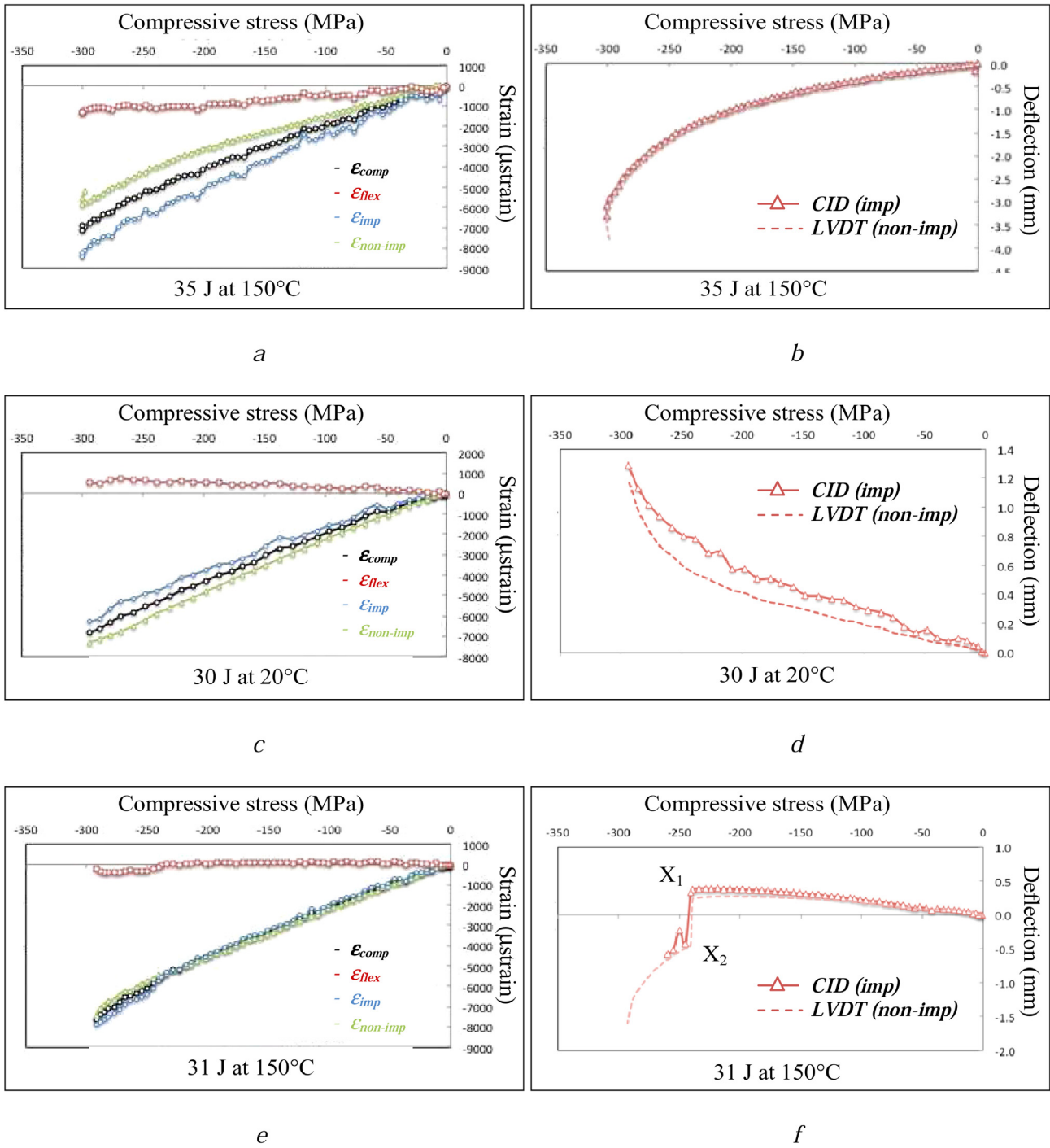


Fig. 10. Three types of CAI response: (a–b) global buckling in the impact direction; (c–d) global buckling in the opposite direction; (e–f) shift in global buckling modes.

failure strain are plotted with respect to the two types of damages highlighted in this paper, namely permanent indentation and delamination (Fig. 14). Of course, such as definition of the equivalent failure strain, a constant ratio exists between this strain and the failure stress.

Surprisingly, one can observe that the extent of the damage has no influence on failure, since every specimen fails around -300 MPa (-6400 μ strain) irrespectively of its damage size. Obviously, the same failure trend is observed when it comes to evaluating the influence of impact energy on the residual strength, as shown in Fig. 15. The maximum CAI stress difference between the impacted samples and the non-impacted sample is only 14%.

The question as to why every impacted sample behaves in compression similarly to virgin laminates in spite of the presence of damage will be discussed in the next section. As for the influence of temperature, the trend lines hardly show any difference between the 150 °C and the RT series.

At least, the final failure scenario is not stable. For non-impacted specimens, the final failure occurs in the upperpart of the plate at -293 MPa (Fig. 16), and is mainly due to global buckling. Fig. 16 shows two other specimens both impacted at 30 J and 150 °C developing two different failure mechanisms during CAI. For the first one, the damage is initiated by the impact-induced damage at the middle of the plate at -321 MPa, due to a mode 1

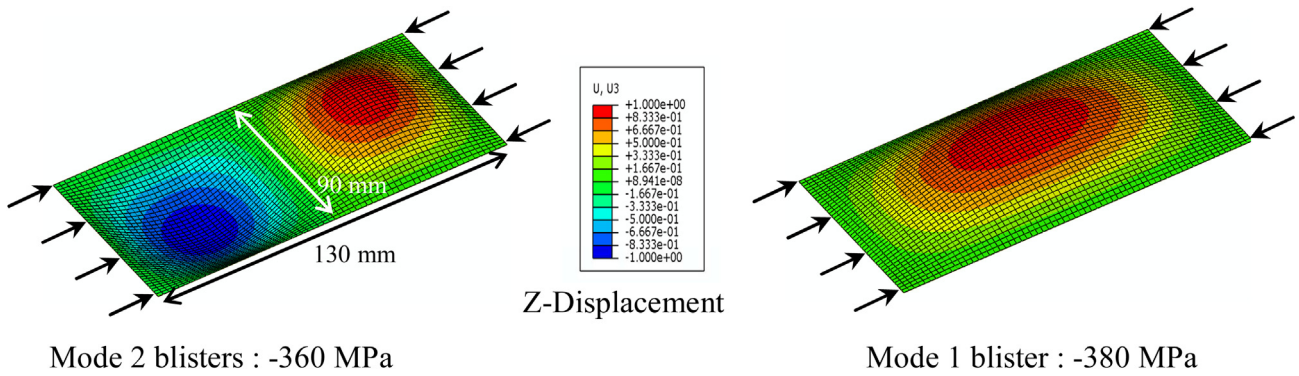


Fig. 11. The 2 first buckling modes.

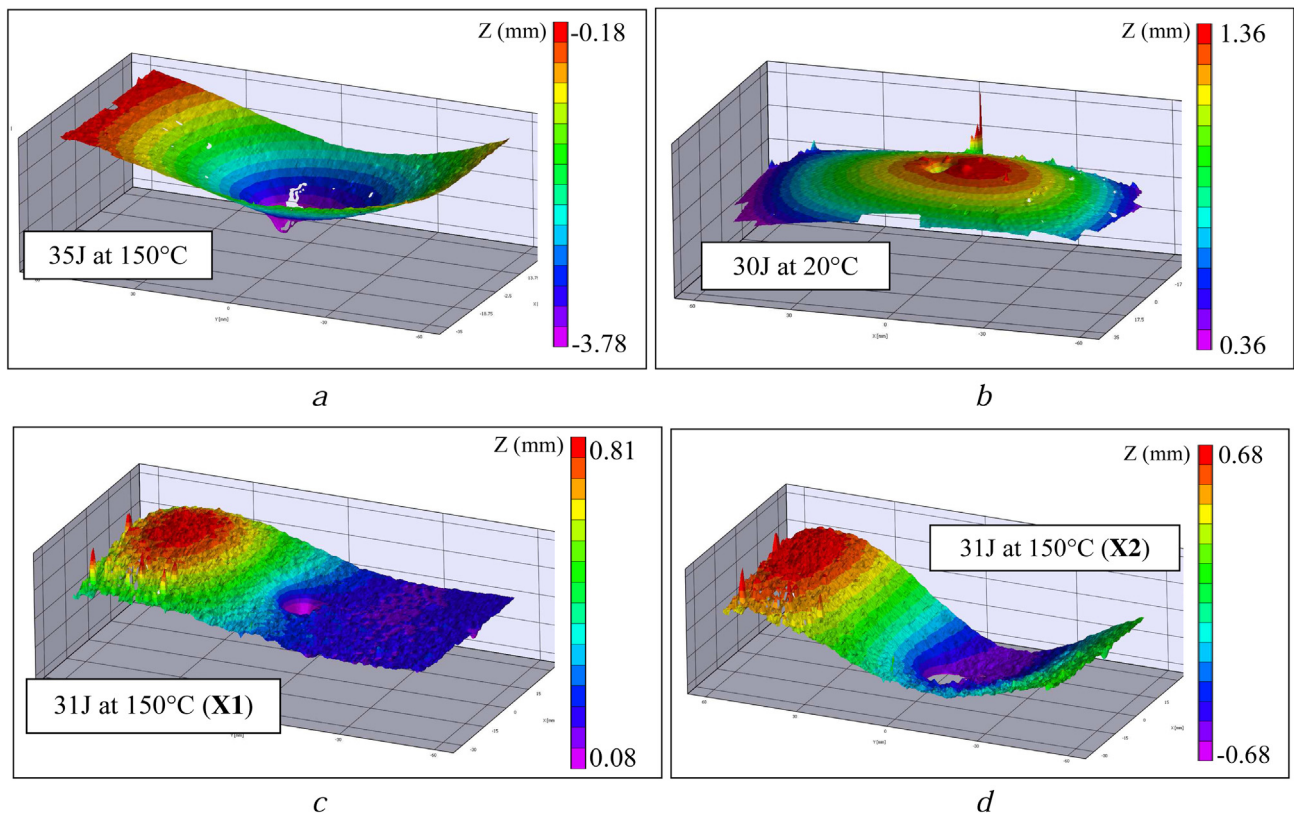


Fig. 12. Z-Displacement of the specimens just before failure – Obtained by DIC technique.

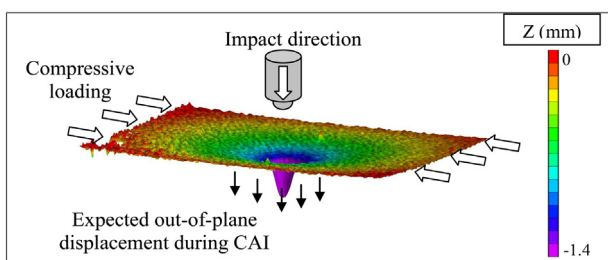


Fig. 13. Expecting out-of-plane displacement during CAI from post-impact laminate's shape.

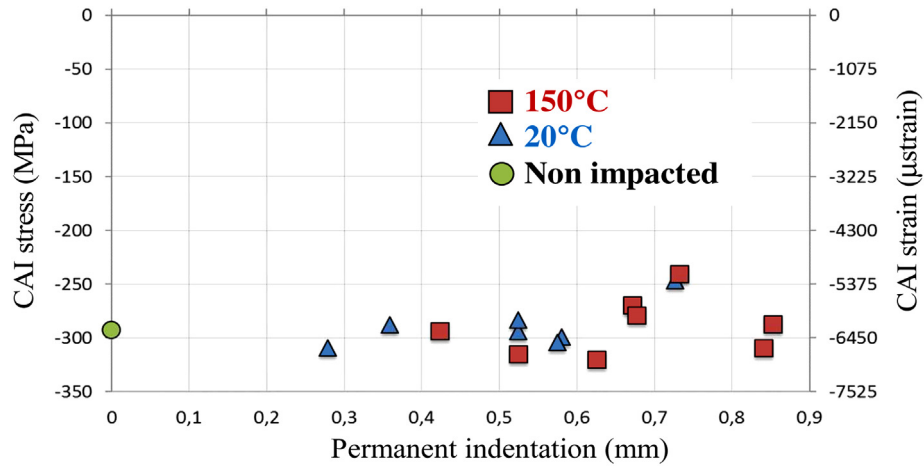
buckling failure, whereas the second mechanism at -270 MPa, due to a mode 2 buckling failure, is similar the non-impacted specimen (also due to a mode 2 buckling mode, Fig. 11). Although the FE cal-

ulation gives a mode 2 buckling prior to the mode 1 buckling, the experimental results are more dispersed. This is of course due to the experimental boundary conditions which are not perfect, such as for the FE calculation, and induces buckling modes depending of little geometry defects.

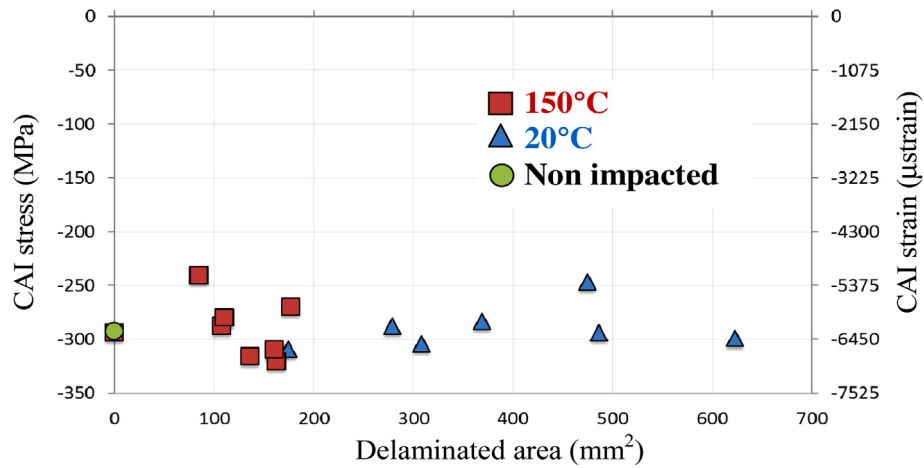
4. Discussion

4.1. Impact behavior

Results reported in Section 3.1 show the effects of temperature onto the impact behavior and more particularly on the damage induced. As seen (Section 3.1.1), maximum force exhibited during impact is somewhat lower at RT than T_g (even if the higher damping at high temperature could explain a part of the difference), while maximum displacements are temperature independent. Fur-



a



b

Fig. 14. Summary of the failure values in function of -a- permanent indentation; -b- delaminated area.

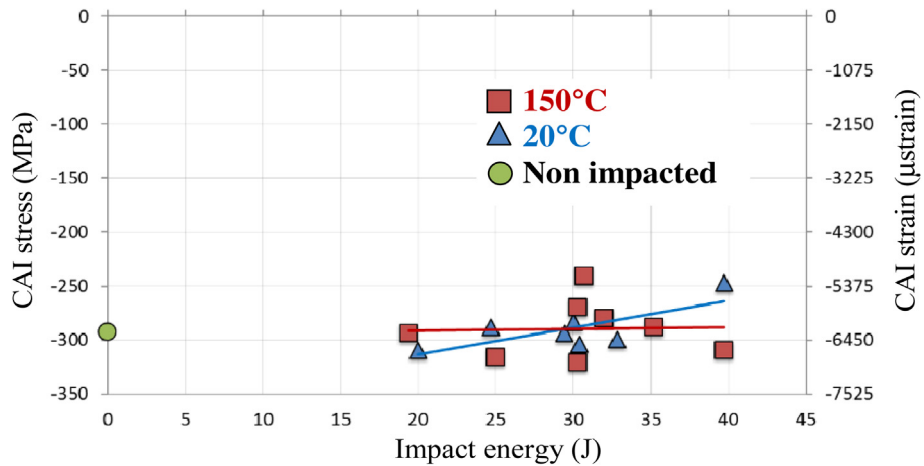


Fig. 15. Summary of CAI stress and strain at failure in function of impact energy.

thermore, laminates impacted at T_g dissipate slightly less energy than RT impacted ones. Dissipation of energy is closely associated with impact-induced damage. Thus, global impact damage is less significant when laminates are impacted at 150 °C. Two damage

indicators are discussed in the sequel: permanent indentation and delamination. Permanent indentation is all the more significant than test temperature is high, as the values obtained are higher for the T_g impact series. As an external visible damage, it

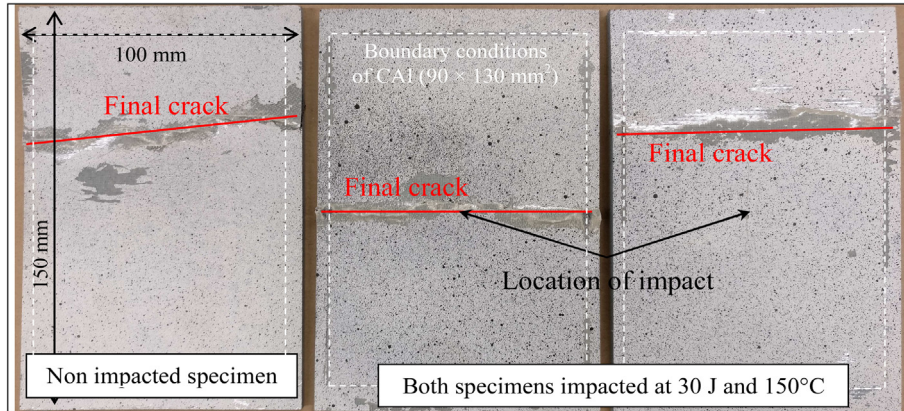


Fig. 16. Comparison of final failure location during CAI of some specimens.

is usually associated with damage detection (BVID). Consequently, if one considers the energy at BVID, it has dropped by 24% from 29 J at 20 °C to 22 J at 150 °C. This result is very interesting because it shows the positive effect of the temperature on the permanent indentation. On the contrary, the reduction of delamination acts the opposite at temperatures around T_g as the propagation of impact-induced damages (intra and inter-laminar cracks) is delayed and slowed down.

As it delays matrix cracking and slows down inter- and intra-laminar crack propagation during fatigue loading, the specific roles of both matrix ductility and toughness [34] should also be observed in TP-based laminates subjected to an impact scenario at a service temperature higher than T_g . Indeed, in addition to the limited propagation of delamination due to the intrinsic toughness of woven-ply laminates [7], temperature has also a non-negligible effect: matrix is tougher and more ductile at high temperature $T > T_g$ what leads to local plastic deformation in matrix-rich region of the laminates before damage appears, resulting in slowing down matrix cracking. On the one hand, it could explain higher values of permanent indentation due to larger plastic deformation, and on the other hand the reduced delamination areas compared with RT impacted laminates. To conclude, the material toughness is enhanced and damage tolerance is improved at $T > T_g$, confirming the conclusions drawn in [7–8].

4.2. CAI response

For a given impact energy (about 30 J) the dispersion of results is significant, but the general tendency remains the same: the ultimate failure seems to be independent of impact energy, and so of permanent indentation and impact induced damages. It is well documented in the literature that woven composites have good damage tolerance when subjected to CAI [7,8]. However, as mentioned in the Results section, all the specimens, irrespectively of their impact energy and damage stress, fail at approximately –300 MPa, or strain at failure –6400 μ strain. In order to discuss this unexpected behavior, another mode of failure, i.e. buckling, was investigated. A FE calculation turns out that the first buckling mode to appear is the mode 2 buckling at around –370 MPa and the mode 1 buckling appears shortly after at around –390 MPa. Then the failure can be expected due to failure inside the sample, and not to global buckling. Nevertheless, the low differences between the numerical buckling stress and the experimental failure stress makes uncertain conclusion on the rupture cause. Moreover, the weak influence of the impact damage on the CAI strength seems confirm the final rupture is not due to impact damage but to a rather global rupture mode, such as buckling.

Nevertheless, it can be highlighted that the equivalent failure strain of –6400 μ strain, obtained in this study, is very high, compared to similar results in the literature where the failure strain is often less (in absolute value) than –4500 μ strain [3,8,12,33]. However, the present study shows that carbon fiber woven TP laminates considered is very tolerant to impact. Two reasons could explain this high damage tolerance: the woven architecture (compared to UD laminate) and the TP resin (compared to TS resins).

Finally, it is difficult to conclude on the effect of temperature on the CAI behavior: to a first approximation the temperature has no effect on the residual strength after impact. This result is very interesting because it allows considering the using of woven TP composite at “high” temperature around the T_g .

5. Conclusions

This experimental work investigates the effect of temperature on impact behavior and damage tolerance of hybrid carbon and glass fibers woven-ply reinforced PEEK TP laminates with a quasi-isotropic stacking sequence. From the results, it appears that these composite materials have a very good impact behavior (high permanent indentation, good impact detectability, and reduced delamination), and a high degree of damage tolerance, even at temperatures close to their glass transition temperature T_g .

When these materials are subjected to low velocity impacts, the effect of temperature on damage propagation and permanent indentation is significant. Indeed, it reduces the dissipated energy especially at low impact energies (20–30 J). Delamination is known to be restricted in woven-ply reinforced laminates, and a temperature increase seems to be instrumental in limiting delamination as the projected delaminated area is nearly 3 times smaller at 150 °C. A second important effect resulting from a temperature increase is a reduction of the impact energy required to induce BVID which is reduced by 24% from RT to T_g , therefore enhancing damage detectability. These mechanisms are closely associated with exacerbated ductility and toughness of high-performance TP around T_g , and more specifically:

- The intrinsic toughness of the fabrics architecture reduces impact-induced delamination;
- Both toughness and ductility of PEEK matrix being enhanced at $T > T_g$, they lead to local plastic deformations delaying matrix cracking, and they slow down inter- and intra-laminar crack propagation.

In order to assess the severity of impact-induced damages on the residual behavior of hybrid woven-ply PEEK laminates, CAI

tests show that the residual strengths are similar with respect to non-impacted laminates, as the compressive failure strength is about 300 MPa, or equivalently the strain at failure is about 6400 μ strain. Surprisingly, the increase in permanent indentation with temperature has no influence on the CAI strength, which seems to be virtually temperature-independent. Matrix toughness being enhanced at T_g , it contributes to the reduction of impact-induced delamination, and this effect of temperature delays and slows down the propagation of impact-induced damages (intra and inter-laminar cracks). From CAI macroscopic responses and the observations of failed specimens, it also appears that failure is primarily induced by global buckling, resulting from significant permanent indentation, even for high impact energies. As a result, impact-induced damages do not influence the CAI residual strength of hybrid G/C PEEK laminates.

However, additional tests should be conducted at both temperatures (RT and T_g) during compression. Indeed, the classical experimental set-up for CAI tests (AITM standard) is not completely appropriate to draw a clear cut conclusion for the studied material as it leads to failure in buckling rather than in damage-driven compression. Due to the material's very good CAI residual strength, another experimental campaign should be carried out with a modified test format in order to restrain buckling effects and to induce damage-driven compression.

Be that as it may, the present experimental study clearly shows that the studied hybrid glass/carbon fibers woven-ply reinforced PEEK TP laminates have a very good impact behavior, and they are very damage-tolerant. Ultimately, the application of these composite materials is particularly relevant for high-temperature applications in aeronautics.

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