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Experimental analysis of the impact behaviour of sandwich panels with sustainable cores

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ABSTRACT

This paper studies the behaviour of sandwiches subjected to impact loads that result in penetration but not complete perforation. The perforation velocity in panels with two different core materials was determined, and the panel response under complete perforation was assessed using 3D-DIC analysis. The out-of-plane displacements were greater in the sandwich with agglomerated cork due to its lower stiffness. The damage and failure mechanisms that appear in both sandwich configurations were also studied using visual inspection and X-ray computed tomography. An explanation of the physics involved in the impact event is proposed based on the qualitative and quantitative analyses of the damage. It was found that the type of core material affected the failure modes that appeared in the sandwich. Skin delamination and skin/core debonding were important failure mechanisms in sandwich panels with a PET foam core, while in sandwiches with an agglomerated cork core, these mechanisms were not observed.

1. Introduction

Composite sandwich structures can be an alternative to traditional structural configurations when high flexural stiffness, strength and low weight are required. They also provide good damping characteristics, thermal insulation, and excellent fatigue resistance. Due to these properties, sandwich structures are widely used in the transport sector sometimes in structural engineering applications.

During their lifetime, sandwich structures can be subjected to impact events such as dropped tools, a stone impacting a high-speed train, a bird strike on an aircraft, etc. The damage produced by the impact can range from an indentation to the complete perforation of the panel.

Understanding their failure modes is important for structural engineering purposes particularly to assess and mitigate impact vulnerability issues. In sandwich panels with a composite laminate skin, apart from the failure modes associated with the laminate (fibre breakage, matrix failure, delamination, etc.), it is necessary to consider the failure modes of the core and those associated with the debonding of the skin-core interface [1–2].

Laminate composites are particularly vulnerable to impacts since they have poor behaviour under transverse loads [3], especially in dynamic conditions that can reduce the stiffness and strength of the complete structure [4]. Delamination is another failure mode that can appear due to the low interlaminar shear strength of the laminate, which is around 1/40 of the in-plane strength [5]. This damage can be internal and may not be visually detected; however, it can produce a significant reduction in the residual mechanical behaviour [2]. Thus, impact strength is a critical design requirement in sandwich structures [6], and impact loads are considered among the most dangerous for a sandwich structure.

The behaviour of the structure under the impact load, as well as its dominant failure modes and damage produced, are associated with the impact velocity of the projectile. An impact phenomenon can be classified as low-velocity impact (LVI) or high-velocity impact (HVI). In a LVI problem, the elastic waves generated by the impact through the sandwich thickness play no role in the stress distribution during the impact process and the structural response of the sandwich is significant [7]. By contrast, HVI events are characterised by the propagation of waves across the sandwich thickness. In this kind of impact, the sandwich is unable to respond globally, the damage is localised, and the boundary conditions play a minor role.

The influence of the boundary conditions is determined by the balance between inertial and kinematic effects that govern wave propagation in different directions. If the wave created at the point of impact reaches the edges of the panel and is reflected back to the impact point during the time of contact, then the impact is considered to be boundary-

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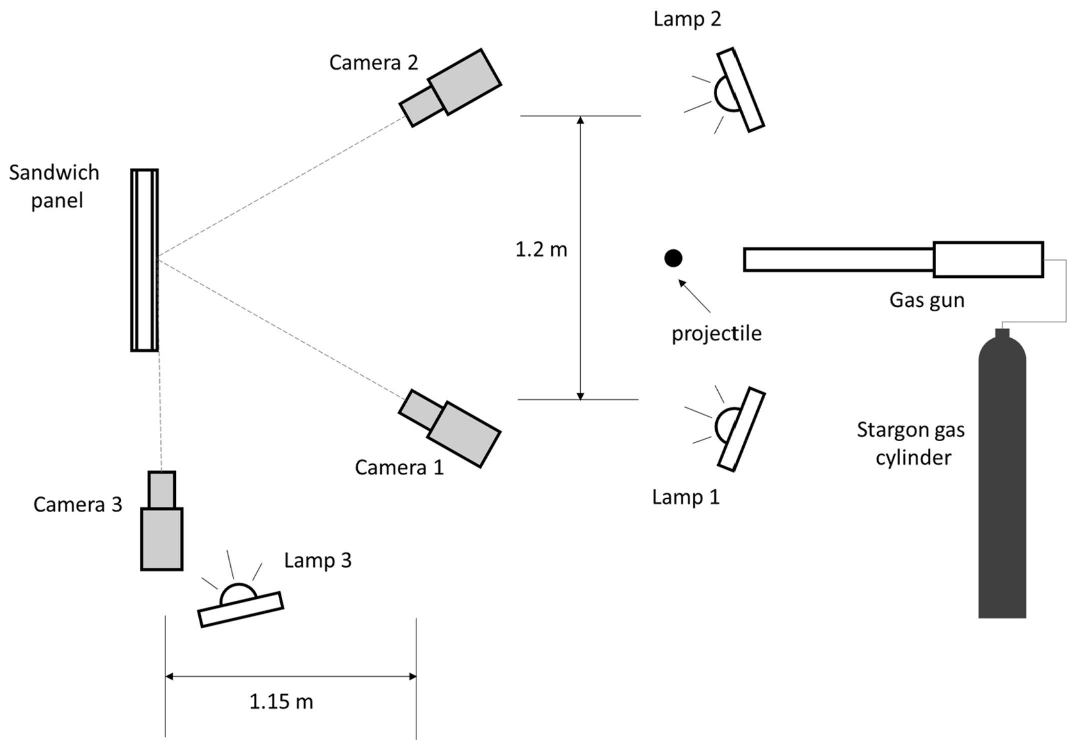

Fig. 1. Representation of the experimental set-up.

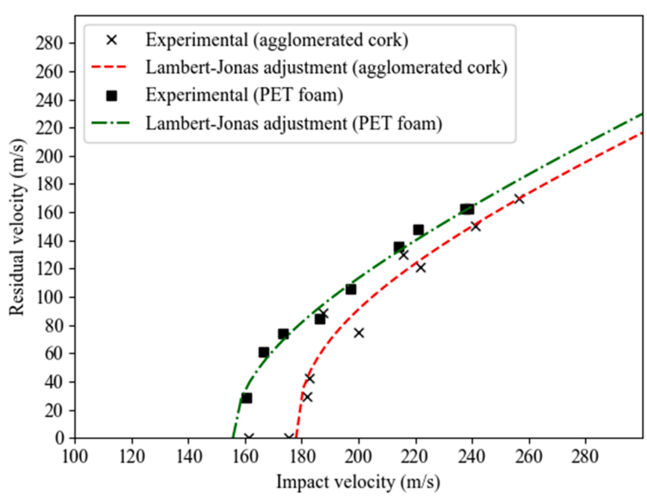

Fig. 2. Residual velocity versus impact velocities in both sandwich panels.

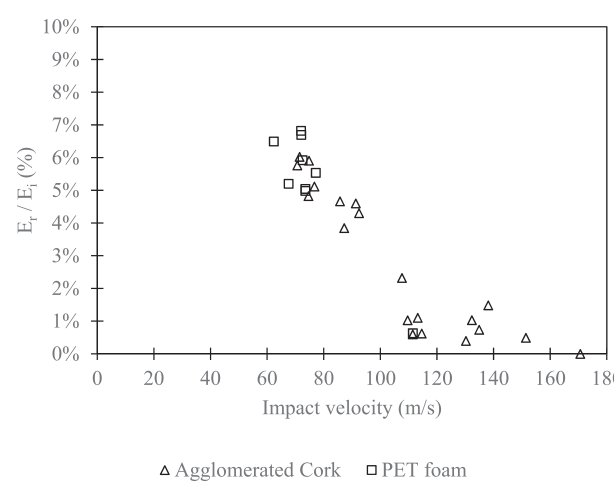

Fig. 3. Ratio of the projectile kinetic energy before and after impact with respect to impact velocity in both sandwich panels.

controlled. On the other hand, if the wave travelling in the plane of the panel does not return to the impact point during the contact duration, but the wave travelling through the thickness is reflected multiple times, the impact is then considered to be wave-controlled.

There is no universally accepted definition of the range of velocities for which an event can be classified as HVI or LVI. Usually, an event is considered to be LVI if the impact velocity is below 10 m/s or even 5 m/s [8], and it is considered to be HVI if the velocity ranges between 100 m/s and 1000 m/s. In between those two categories, there is a transitional category in which the physical mechanisms taking place are a combination of those found separately in both types of events. This region would occur, at impact velocities of between 50 and 150 m/s, depending on the projectile and panel sizes. Bird strikes or hail impacts that affect commercial aviation aeroplanes, wind turbine blades or high-speed trains are often classified as transitional between LVI and HVI.

The behaviours of sandwich structures with polymeric foam cores or honeycomb cores subjected to LVI [9–12] or HVI [6,13–16] have been extensively studied. However, fewer studies are available on impact velocities between 10 and 100 m/s [17–19].

Different types of materials can be used for manufacturing the cores of a sandwich structure. For many industrial applications in the energy, automotive or naval industries, polymeric foams are the preferred materials due to their properties and cost. These properties include having good specific mechanical strength, being resistant to moisture and water, and being unaffected by various chemicals.

Conventional polymeric foams are synthetic materials manufactured from non-renewable sources and generate waste at the end of their service life. This raises concerns about the environmental impact of such industrial processes and the sustainability of resources, prompting the search for sustainable alternatives. An alternative to reduce the environmental impact of foam cores is to use natural materials or materials

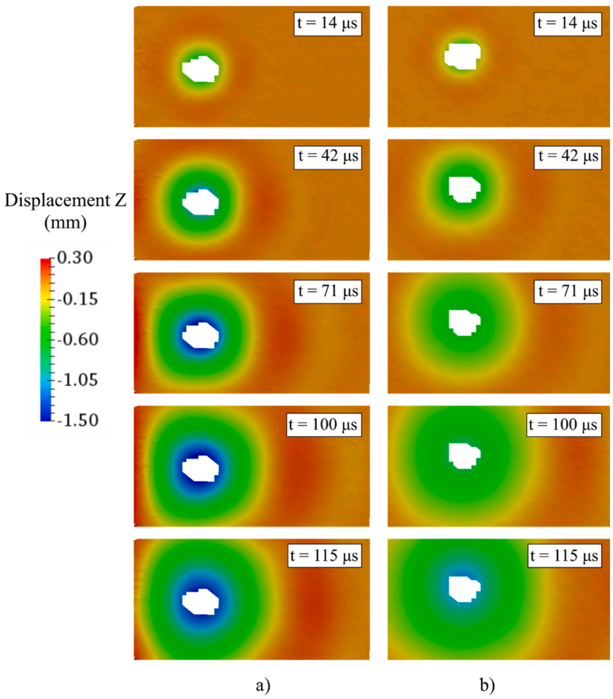

Fig. 4. Out-of-plane displacement at several instant of time. Sandwich panel with agglomerated cork core. a) Impact velocity 71.5 m/s, b) Impact velocity 135 m/s.

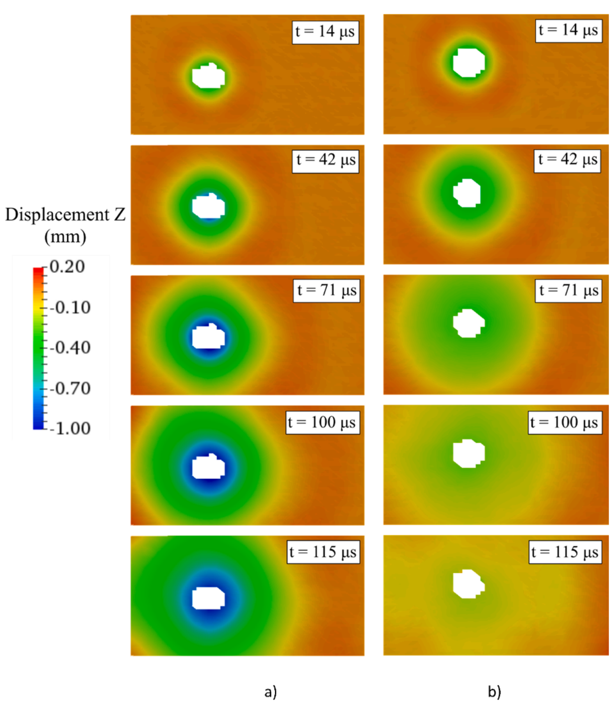

Fig. 5. Out of plane displacement at several instant of time. Sandwich panel with PET foam core. a) Impact velocity 72.5 m/s, b) Impact velocity 138 m/s.

made of recycled waste. A candidate core material must also have low density, high acoustic insulation, low thermal conductivity, and relatively high shear stiffness. Attending to these requirements, this work studied two promising core material alternatives: agglomerated cork and PET foam.

Agglomerated cork is a cellular material made of natural cork granules mixed with a little amount of polymeric resin. Due to its natural origin, it is a sustainable and easily recyclable material made from the waste of the cork industry (for example from the manufacture of cork stoppers) that can be reused. Additionally, since it is a mixture, the effect of anisotropy produced by natural cork is reduced by combining granules with random orientations. Agglomerated cork also has good damping capacity and excellent damage tolerance, combined with low density and cost [20,21]. Despite this, for certain grain sizes and densities, agglomerated cork may have worse mechanical properties than some polymeric foams. Agglomerated cork, for example, may have better specific mechanical properties than flexible foams and is comparable to rigid foams [22] but unlike rigid foams, it has high dimensional recovery [23].

The other material studied in this work, polyethylene terephthalate (PET) belongs to the polyester family and it is one of the most commonly used thermoplastic polymers. Around 20 % of the world's production of polymer materials is polyester. PET is used for multiple applications, for example by the packaging industry (around 30 % of global production). There is an increasing interest in using this material as a foam core for sandwich structures due to its high specific strength and stiffness, as well as its low thermal conductivity [24]. Additionally, PET foam can be made of recycled elements (such as bottles or other packaging), which may have an important impact on reducing municipal waste.

The properties of the core material in a sandwich structure modify the behaviour of the sandwich structure under impact loads [25–28]. As a result, conclusions obtained for a sandwich with a polymeric foam core, for example, polyvinyl chloride (PVC) or polyurethane (PUR) foams, are not necessarily applicable to sandwiches with agglomerated cork or PET foam cores. Additionally, it is hard to compare the impact behaviour between sandwich structures with different cores, obtained from separate studies, since the impact parameters (panel geometry, core thicknesses, projectile, boundary conditions, etc.) are different.

Relatively few studies have been carried out on the behaviour of sandwiches with agglomerated cork as a core subjected to impact loads. Some of them studied sandwiches with skins made of carbon/epoxy [29], flax/epoxy [30–33], flax/basalt/polypropylene [34] and with jute/epoxy skins [35], analysing them under static and dynamic conditions. Most of these works were focused only on LVI events, while much less is known about the behaviour of sandwiches with agglomerated cork to impacts over 50 m/s [35,13,36,37]. Despite this, studies have shown that agglomerated cork is a promising alternative to synthetic foams as a core material. Regarding sandwich structures with PET foam cores, there are some references in the scientific literature, but they are comparatively fewer than for other types of foams, and most of them are focused on LVI events [38–41].

No comparisons of the impact behaviour of sandwiches with PET foam and agglomerated cork cores were found in the literature and there is not enough information on the perforation process and damage evolution in these sandwiches. Therefore, this work presents an experimental study of the impact behaviour of sandwich structures with PET foam and agglomerated cork cores for impact velocities that do not completely perforate the front panel. The influence of the core material in the out-of-plane displacements and in-plane strain distribution was studied using a 3D Digital Image Correlation (DIC) analysis. Velocities above and below the velocity that causes the perforation of the front skin were selected. Differences in failure mechanisms for the same impact velocities were also studied, using visual inspection and X-ray tomography.

2. Materials and methods

The sandwich panels used in this work were manufactured by a company specialized in the production of aeronautical structural elements (Aerotecnic) following aeronautical standards as suggested by the data sheet of the materials. These panels are composed of skins made of a carbon/epoxy fabric laminate with a [90/0/±45]s stacking sequence. AS4/8552 carbon/epoxy plies from Hexcel Corporation were used to

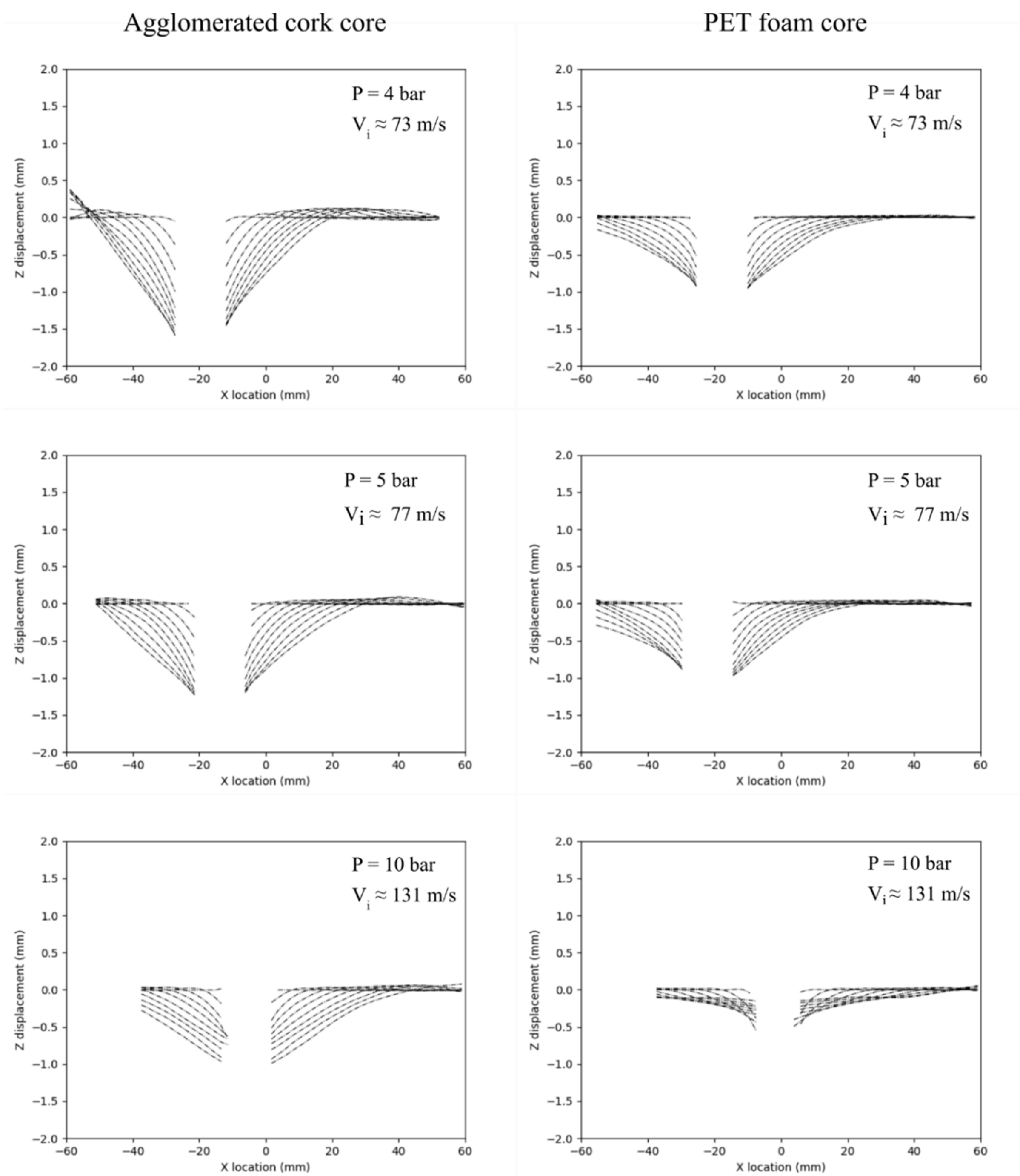

Fig. 6. Deflection shape during the first 120 μs after impact measured by 3D-DIC analysis. Sandwich with agglomerated cork core (left) and PET foam core (right). Impact velocities between 73 m/s, 77 m/s and 131 m/s.

manufacture the laminate. Two sustainable core materials were selected: an agglomerated cork (NL20 CORECORK with a density of 215 kg/m^3) manufactured by Amorin Cork Composites; and a polyethylene terephthalate (PET) foam manufactured by the company AIREX (T92.200 with a density of 211 kg/m^3). Both core materials as received without any modifications were used to prepare the sandwich panel. Square specimens of 120 mm × 120 mm and 8.6 mm thickness were used.

Impact tests were performed using a Sabre Ballistic gas gun firing spherical steel projectiles of 7.98 g mass and 7.5 mm diameter. Stargon gas (a mixture of Argon gas, CO_2 and O_2) was selected as propellant gas to achieve the desired range of impact velocities.

Two Photron FASTCAM SA-Z high-speed cameras in stereo configuration were used to record the tests at 70,000 fps with a spatial resolution of 512 × 496 pixels and a time of exposure of 1/400 ms. Both cameras were equipped with Tokina MACRO 100 f2.8D lenses. The purpose of these cameras was to record the impact event and provide the required input frames for the stereo 3D-DIC analysis. A third high-speed camera (Photron Ultima) was positioned perpendicular to the projectile trajectory, focused on the impact location and recording at the same frame rate as the other two cameras, Fig. 1. The recording from the third camera was used to estimate the impact velocity, as well as the rebound or residual velocity, using an image tracking algorithm. In addition, this camera provided a perpendicular view of the impacted specimen that helped to analyse the impact event. The gas gun was aligned with the centre of the specimen using laser levels.

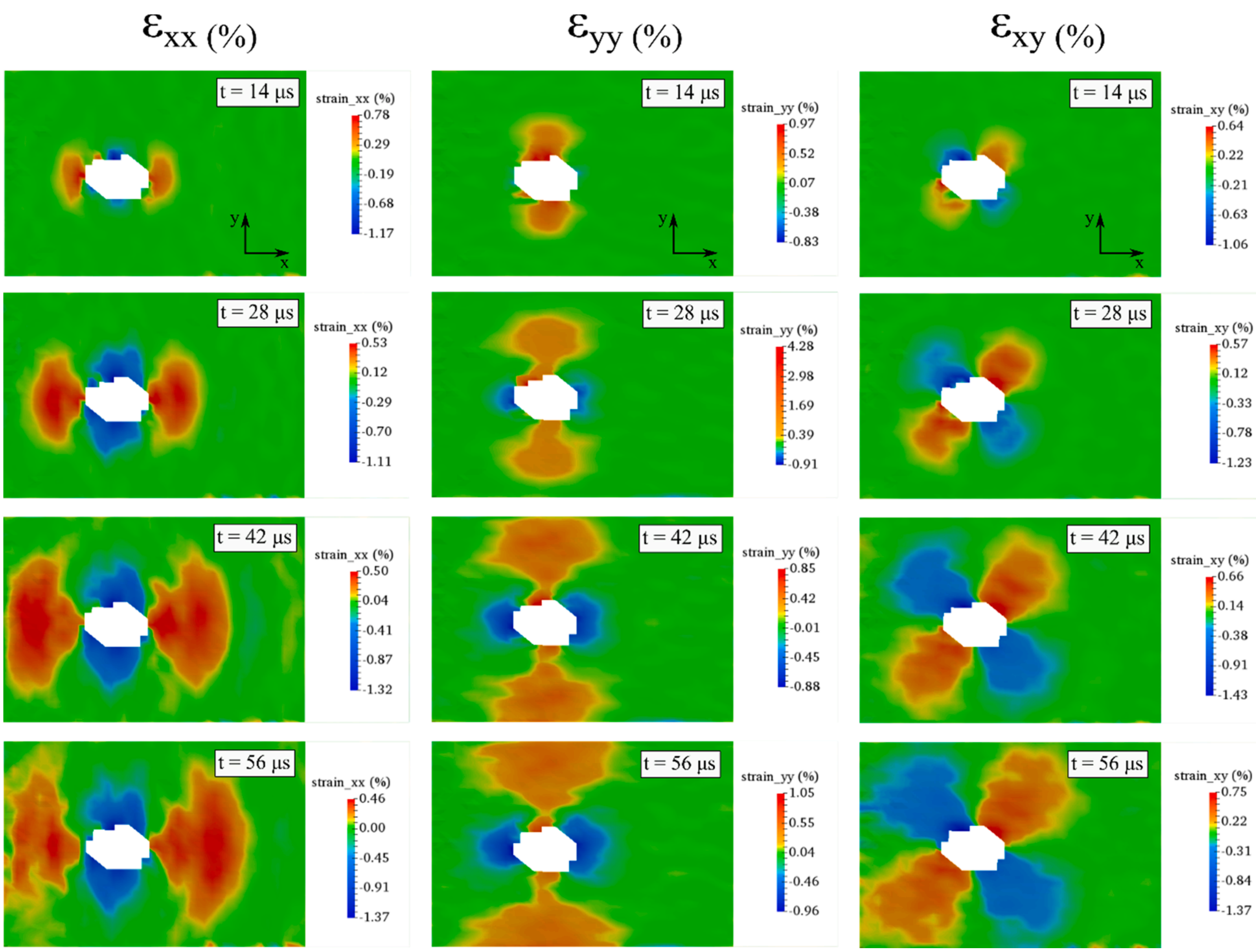

Fig. 7. In-plane strains of the front skin around the impact location (ply 8) during the first instants after impact measured with DIC. Sandwich panel with an agglomerated cork core, impact velocity 71.5 m/s.

In order to study the partial penetration of the sandwich panels, the perforation velocity (impact velocity at which complete perforation of the panel occurs) was estimated. Impact tests in a broad range of impact velocities were carried out, Fig. 2. The perforation velocity was calculated by fitting the Lambert and Jonas equation [42] to the experimental data by the least squares method. The perforation velocity for sandwich panels with agglomerated cork core was calculated to be 178.4 ± 1.5 m/s and that for PET foam core sandwich panels was 159.4 ± 0.9 m/s, a difference of 14 %. The difference in perforation velocities may be due to the different mechanical behaviours of PET foam and agglomerated cork (elastic–plastic vs hyperelastic behaviour) [43].

This study on the impact event and the damage mechanisms of sandwich panels without complete perforation used impact velocities between 60 m/s and the perforation velocity.

Stereo 3D-DIC was used to estimate the in-plane strains and out-of-plane displacements in the front skin of all panels. The speckle pattern was generated with spray paint using an airbrush as recommended in [44].

The Digital Correlation Engine V.2 software, developed by SANDIA National Laboratory, was used in this study. The subset size (21 pixels) was selected according to the speckle size (average size 1 mm) ensuring that at least three speckles were covered by a single subset, and the step size (8 pixels) was chosen to obtain enough spatial resolution and low computational time. Calibration was performed by taking multiple images to a dotted grid with a spacing of 8 mm varying its orientation with respect to both cameras. The transformation matrix and the lens distortion parameters were obtained with minimum epipolar error. The same calibration file was used for all DIC analyses. All the previously mentioned parameters provided good correlation and spatial definition; the maximum correlation error was 2.9 % with a measurement error lower than 2 μm.

In order to understand the impact event, and especially the energy absorption mechanisms, it is necessary to analyse the morphology of the damage. In this work, the X-ray computed tomography (XCT) technique was used to capture the characteristics of the damage in detail. Due to the size of the specimens, the field of view (FOV) was limited to a portion of the total length, which included the area affected by the impact. A Tungsten target in mode 0 was used with 120 kV voltage and 60 μA current. The scanner took 3000 images per specimen with a resolution of 27.7 μm/pixel. The lateral faces of the panels were also aligned for better analysis. The images obtained from the XCT were processed and analysed using the Image J software

3. Results and discussion

3.1. Impact behaviour

From the tests carried out below the perforation velocity, significant influences of the core material in the rebound of the projectile were observed. In sandwich panels with an agglomerated cork core, a rebound of the projectile occurred on impacts without complete perforation of the panel. The projectiles were never trapped inside the panel, even when the front skin was perforated. By contrast, in PET foam core sandwich panels, the projectile rebounded at impact velocities lower

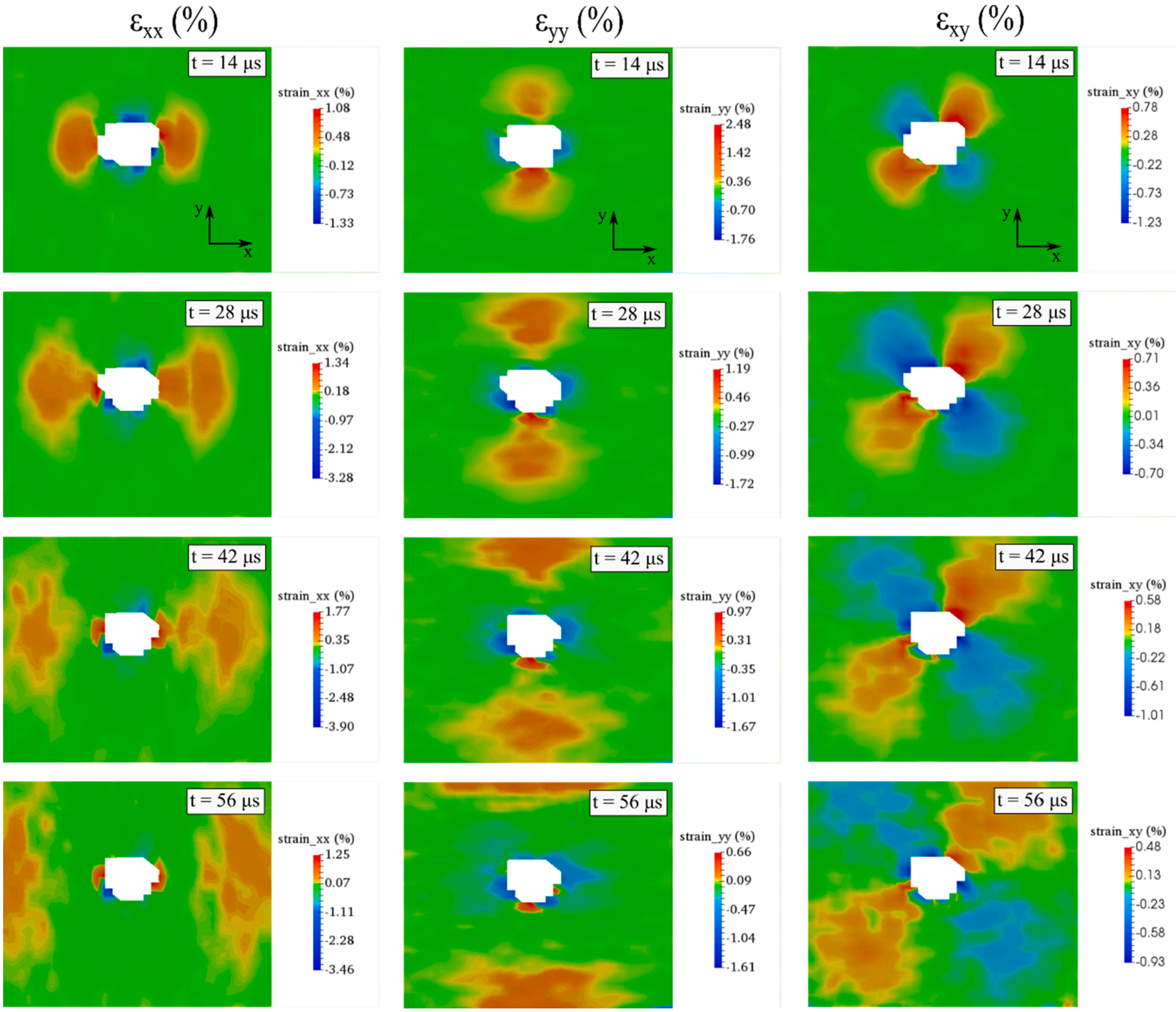

Fig. 8. In-plane strains of the front skin around the impact location (ply 8) during the first instants of time after impact measured with DIC. Sandwich panel with an agglomerated cork core, impact velocity 135 m/s.

than 73 m/s at which the front skin was not perforated. However, in those cases when perforation of the front skin occurred, the projectile was trapped inside the sandwich. This difference in behaviour is associated with the mechanical properties of the core material [43]. In agglomerated cork, the material showed high elastic return even after large deformations while in PET foam due to its semi-rigid nature, the material response was dominated by plastic crushing with very little elastic recovery.

In those cases where projectile rebound occurs, the projectile recovered part of the initial kinetic energy in the spring back and its magnitude was estimated by measuring the rebound velocity using the record from camera 3 and the tracking software. Fig. 3 shows the ratio between the projectile kinetic energy before and after impact as a function of impact velocity. This ratio decreased with increasing impact velocity, going to zero as the impact velocity approached the perforation velocity. This evolution has been observed previously in sandwich plates with an aluminium honeycomb core [45]. These authors found values of this ratio between 0.01 and 0.04 for velocities close to perforation, for different core thicknesses and skin materials.

Both sandwich panels recovered from 4 % to 7 % of their initial kinetic energy for impact velocities below 100 m/s. Sandwich panels with the PET foam core showed slightly higher kinetic energy ratios than sandwiches with an agglomerated cork core. However, data variability prevented reaching a definitive conclusion about the influence of the core material on the energy dissipation ratio. From the same figure, it is observed that the kinetic energy ratio was around or less than 1 % in impact events over 100 m/s probably due to non-conservative energy dissipation mechanisms, such as plastic dissipation and panel damage.

The distribution of out-of-plane displacements in the external surface of the front skin around the point of impact was estimated by 3D-DIC analysis. Figs. 4 and 5 show a top view of the panel, presenting the out-of-plane displacements as colour maps in the first 120 μs after impact. Two impact conditions below the perforation velocity are shown. The impact velocities were selected to ensure that no perforation of the frontal skin occurred (71.5 m/s and 72.5 m/s for the agglomerated cork core sandwich and foam PET core sandwich respectively) and that perforation of the frontal skin occurred but without complete panel perforation (135 m/s and 138 m/s respectively). In addition to the top view, a cross-sectional view of the out-of-plane displacement in the centre section of the specimen is shown in Fig. 6. This figure depicts the displacement shape at equally spaced time intervals ($\Delta t = 14.2$ μs) for both sandwich panels at three impact velocities, 73, 77 and 131 m/s. In these three figures, it was not possible to get information on the point of impact due to the shadow produced by the projectile on the panel.

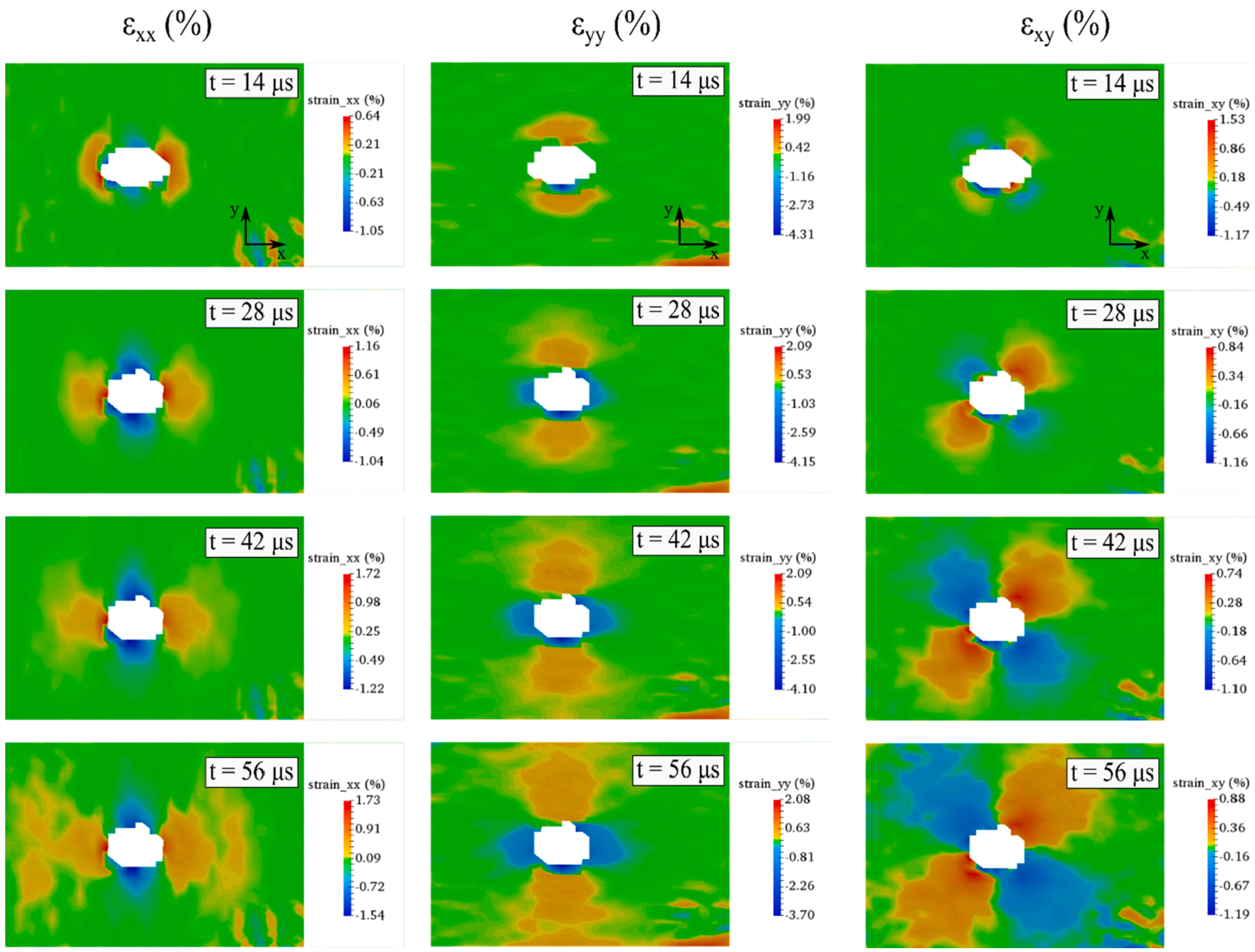

Fig. 9. In-plane strains of the front skin around the impact location (ply 8) during the first instants of time after impact measured with DIC. Sandwich panel with PET foam core, impact velocity 72.5 m/s.

Nevertheless, it was possible to obtain accurate information on the out-of-plane displacement in the area around the impact point.

As expected, the magnitude of the out-of-plane displacement was maximum at the impact site and increased with time as the stress waves propagated radially outwards. Also, it can be observed that the magnitude of the displacement changed with the impact velocity. The out-of-plane displacements were larger for the lower impact velocities than for the higher velocities. This effect is due to the influence and severity of local failure during penetration at higher impact velocities. For example, at the lowest impact velocities studied, the front skin was slightly damaged. Therefore, the complete front skin behaved like a continuous body deflecting together with the advancing projectile. On the other hand, at higher impact velocities, the impact produced a massive failure of the plies directly in contact with the projectile. This failure propagated through the thickness and eventually, the front skin broke apart and two areas appeared: the area furthest away from the impact location and a detached plug. The farthest region was unable to keep deflecting with the projectile and started oscillating due to the initial disturbance. On the other hand, the detached plug, roughly the size of the projectile, kept moving together with the projectile.

The magnitude of the out-of-plane displacements in the front skin is also dependent on the core material. As can be observed in Fig. 6, the magnitude of displacements was larger for agglomerated cork core sandwiches than for those with PET foam core, tested at roughly the same impact velocities. This is caused by the difference in the stiffness and plateau stress between both materials, as observed in previous studies published by the authors [43,46,47]. These works show that the dynamic Young modulus of the PET foam (139 MPa) is more than 10 times larger than the agglomerated cork (11.6 MPa). Similarly, the plateau stress of PET foam (5.57 MPa) was almost 5 times larger than for agglomerated cork (1.14 MPa). As a result, the front skin with the PET foam is expected to have a more rigid foundation and less out-of-plane displacement.

The in-plane strain distribution around the impact point was also analysed during the first 56 μs after impact for both sandwich panels and at two different impact velocities (Figs. 7 to 10). The strain distribution was not uniform but was instead characterized by an orthogonal distribution in which compressive and tensile longitudinal strains (ε_{xx}, ε_{yy}) were aligned with the orientation of the fibres at 0° and 90°. Meanwhile, positive and negative shear strains (ε_{xy}) were also orthogonally distributed but were aligned at 45° to the orientation of the fibres. The strain was distributed in a lobular shape around the impact point with strain levels decreasing with the distance from the impact location. The maximum longitudinal strain (ε_{xx}, ε_{yy}) occurring in the PET foam core sandwich panel was significantly greater than in the agglomerated cork core sandwich. Thus, the maximum ε_{yy} for a time of 56 μs was twice that of the cork core sandwich panel. By contrast, the maximum shear strain was similar in both sandwich panels.

In Figs. 7 and 9 the impact velocity was not sufficiently high to perforate the front skin, while in Figs. 8 and 10 perforation occurred. The penetration of the front skin produced a difference in the propagation of the strain field as the impact progresses. For example, for the no perforation condition, the strain propagated radially and continuously as the impact proceeded. However, when the front skin was

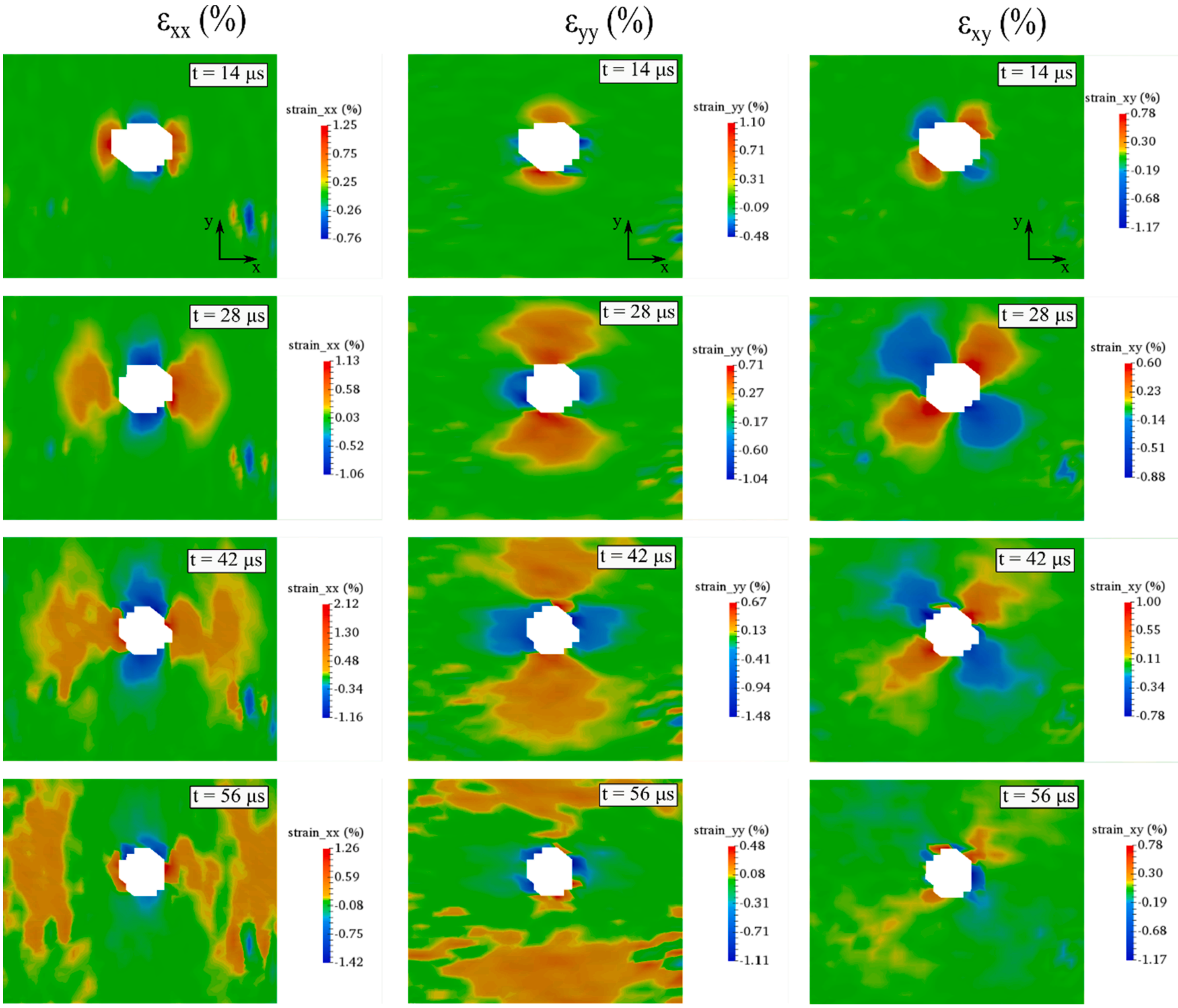

Fig. 10. In-plane strains of the front skin around the impact location (ply 8) during the first instants of time after impact measured with DIC. Sandwich with PET foam core, impact velocity 138 m/s.

perforated, the propagation of the strain disturbance was suddenly interrupted once massive fracture in the impact region and the plug appeared. At this point, the continuity of the skin was lost and no further strain is transmitted from the impact point. This effect can be visualized in Figs. 8 and 10 for impact times t = 42 µs and t = 56 µs where disturbances of the strain field seem to stop around the impact point. When the front skin is perforated, the maximum values of the strain field were similar for both types of sandwiches for a time of 56 µs, with no consistent trend between the different strain components.

3.2. Damage and failure morphology

Damage along the thickness of both sandwich panels was optically analysed by cutting the panels transversely. Fig. 11 shows the mid-cross-section of both panels impacted at three different velocities below complete perforation. Relatively localized damage around the point of impact was found. As can be observed, at impact velocities around 71 m/s, both panels showed indentation of the front skin accompanied by a localized core compression under the impact point. In the case of PET foam core panels, local crushing was visible in the core-front skin interface in the area close to the impact location (Fig. 11, top right image). No visible crushing was observed in panels with the agglomerated cork core impacted at this velocity (Fig. 11, top left image). This phenomenon may be due to the high elastic recovery observed in agglomerated cork when subjected to compressive loads [48]. In both panels, the optical images show that the plies closest to the core-skin interface seemed to have failed due to fibre breakage. Additionally, the X-ray images (Fig. 12) showed delamination in the top skin in this range of impact velocities. These two damage modes are typical of a non-penetration impact on a laminate.

At impact velocities close to 113 m/s, both panels were heavily damaged by the formation of a crater that penetrated the core. This crater originates from the failure of the frontal skin that allows the penetration of the projectile into the core. In a laminate made of fabric plies, this damage to the impact face has a cruciform shape when a complete penetration of the laminate has not occurred. This pattern is related to the membrane stress that causes a tensile fracture in the direction of the fibres [49]. A cross-shaped damage pattern has been observed at high and low velocities in laminates and sandwich structures before [49,50]. During the penetration of the projectile into the skin and the core, the damaged area (delimited by the arm of the cross) tilt in towards the core, forming the crater that can be seen in Fig. 11. The formation of the cross-shaped damage is also accompanied by delamination in the front skin which extends beyond the projectile diameter

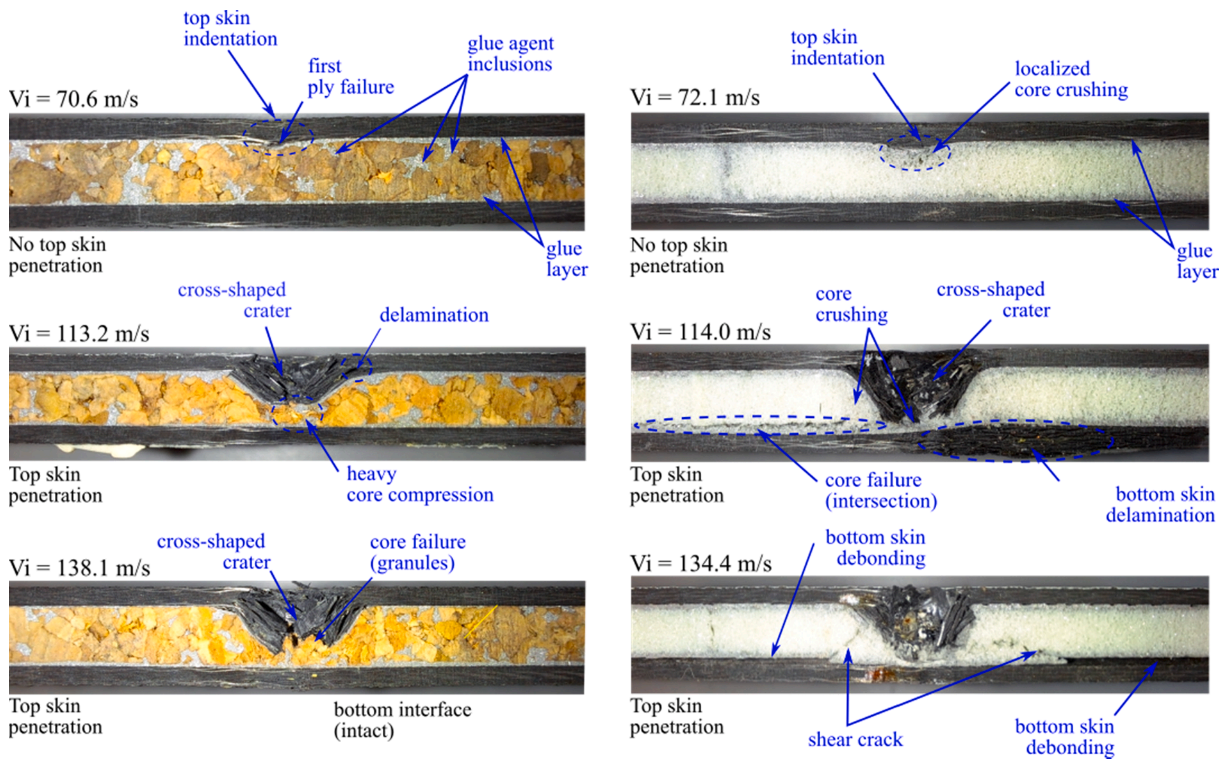

Fig. 11. Post-impact damage. Cut-section of test specimens impacted at three different velocities. Left: Sandwich panels with an agglomerated cork core. Right: Sandwich panels with PET foam core.

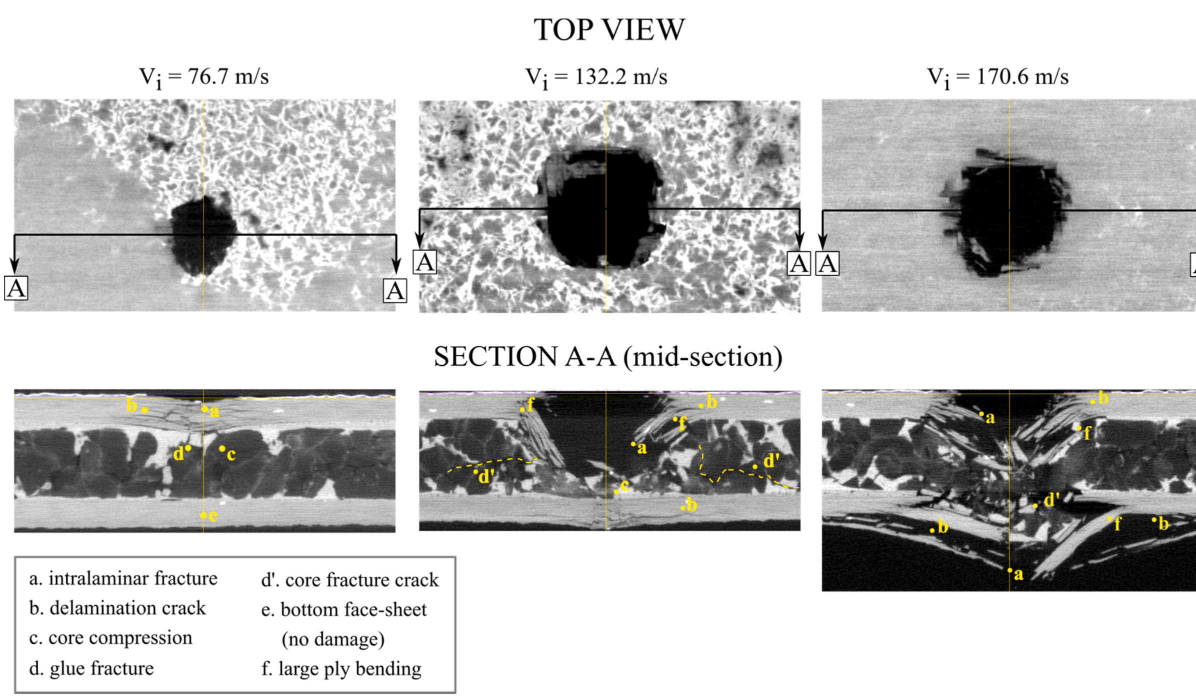

Fig. 12. Post impact damage for three impact velocities. X-ray computed tomography across the mid-section. Sandwich panels with an agglomerated cork core.

and the crater region. This cross-shaped crater also compresses the core laterally, something that was visible in the crushed PET foam core around the crater. It is also clearly visible that both cores were highly compressed by the projectile advance in the direction of the projectile forward movement (along the thickness of the panel). In the PET foam core sandwich panel, the projectile penetration appeared larger than in the agglomerated cork core sandwich and the crushed region in the core appeared to have become more dense and fragmented. In contrast, the agglomerated cork core was also highly compressed but kept its integrity without fracturing or fragmenting.

In the PET foam core sandwiches, when the impact velocity was increased, shear cracks appeared in the core, which resulted in a cone-shaped damage shape. This phenomenon was very evident in impacts at 134.4 m/s (Fig. 11, bottom right image). When these cracks reached

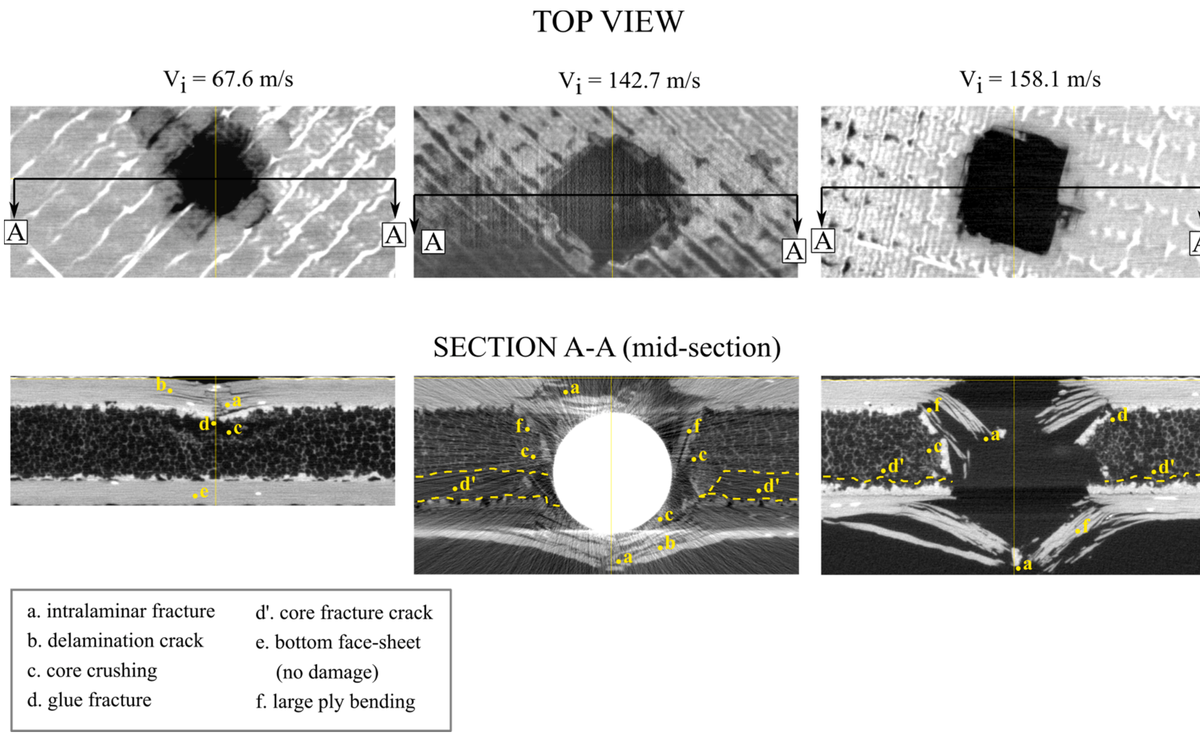

Fig. 13. Post impact damage for three impact velocities. X-ray computed tomography across the mid-section. Sandwich panels with PET foam core.

the bottom skin, a large crack appeared in the skin-core interface that produced the debonding between skin and core. This behaviour was observed by other researchers who studied sandwiches with different foam cores and epoxy-based woven skin laminates subjected to low and high-velocity impacts [51,52]. The debonding can be also related to a weak bond between the foam core and carbon/epoxy laminate [52]. In some of the tests at impact velocity over 114 m/s, extensive delamination in the bottom skin appeared (Fig. 11, middle right image).

In the agglomerated cork core sandwich, the weakest points in the core are at the interface between the natural cork granules and the binder [53], which is where the failure starts in the whole area around the point of impact. The crack changes its direction every time it encounters a cork granule and thus, shear cracks do not appear in this sandwich at any impact velocity.

Similar results are obtained from XCT inspection and are shown in Figs. 12 and 13 for sandwich panels with an agglomerated cork core and PET foam core respectively. These figures show the top view of the impacted specimens and the mid-cross-section of the panel at three impact velocities.

The impact velocities were selected to show three different levels of damage. At the lowest impact velocity (76 m/s for panels with an agglomerated cork core and 67 m/s for panels with PET foam core), the indentation in the front skin was small (approximately 0.5 mm in both panels) and it could be undetectable by the naked eye. However, as shown in the midsection images there was a considerable amount of damage dominated by intra-laminar ply fracture and multiple delaminations in the front skin that extended radially beyond the indentation crater. Fracture of the adhesive also appeared at the intersection of the core with the front skin forming a crack that led to debonding. Core compression was also observed in both core materials, however, the PET foam seemed to suffer from premature crushing and fragmentation while the agglomerated cork seemed to sustain compression without any apparent failure. No damage was observed in the back skin for any of the sandwich panels under the impact velocities shown in Figs. 12 and 13.

At higher impact velocities (132 m/s for panels with an agglomerated cork core and 142 m/s for PET foam core panels), there was complete penetration of the front skin and massive core damage on both panels. Complete ply intra-laminar failure led to large bending of individual plies which in turn formed the cross-shaped damage pattern described previously. These cross-shaped patterns compress the core laterally, crushing PET foam cores. Large cracked regions were observed across both core sections. Indeed, for the PET foam core, the cracked regions encouraged a massive separation of the core and back skin. At these impact velocities, much delamination and some intra-laminar failure appeared in the back skin but not perforation.

Finally, at the highest impact velocities (170 m/s for panels with an agglomerated cork core and 158 m/s for PET foam core panels) there was generalized damage across the panel thickness similar to that described for the previous velocity range. The greatest difference, though, was the accompanied visible intra-laminar failure in the back skin.

From the data obtained in X-ray tomography, it was possible to estimate the delamination area in the skin. In this work, this area was estimated by projecting the pixels with the minimum intensity along the vertical direction (top view). The area was measured using the Image J software. Fig. 14 shows the delamination area for sandwich panels with agglomerated cork and PET foam cores at the same impact velocities discussed previously. For all impact conditions tested and in both sandwich panels, the delamination area in the front skin was observed to have a roughly circular shape centred at the impact point, which extended radially beyond the crater diameters (darker pixels). From the studied specimens, the delamination area in the front skin seemed to increase with impact velocity. This behaviour has previously been observed in monolithic laminates [54].

No delamination occurred in the back skin if there was no perforation of the front skin and the damaged area in this skin was small. This behaviour appeared for the lowest impact velocities shown in Fig. 14. For impact velocities that resulted in perforation of the front skin, delamination appeared on the back skin. At the highest impact velocities, the damaged area in the back skin was significantly larger than in the front skin for both sandwich panels. This behaviour was also observed in the impact on monolithic plates. At these impact velocities, the damaged area in the front skin was similar in both sandwich panels.

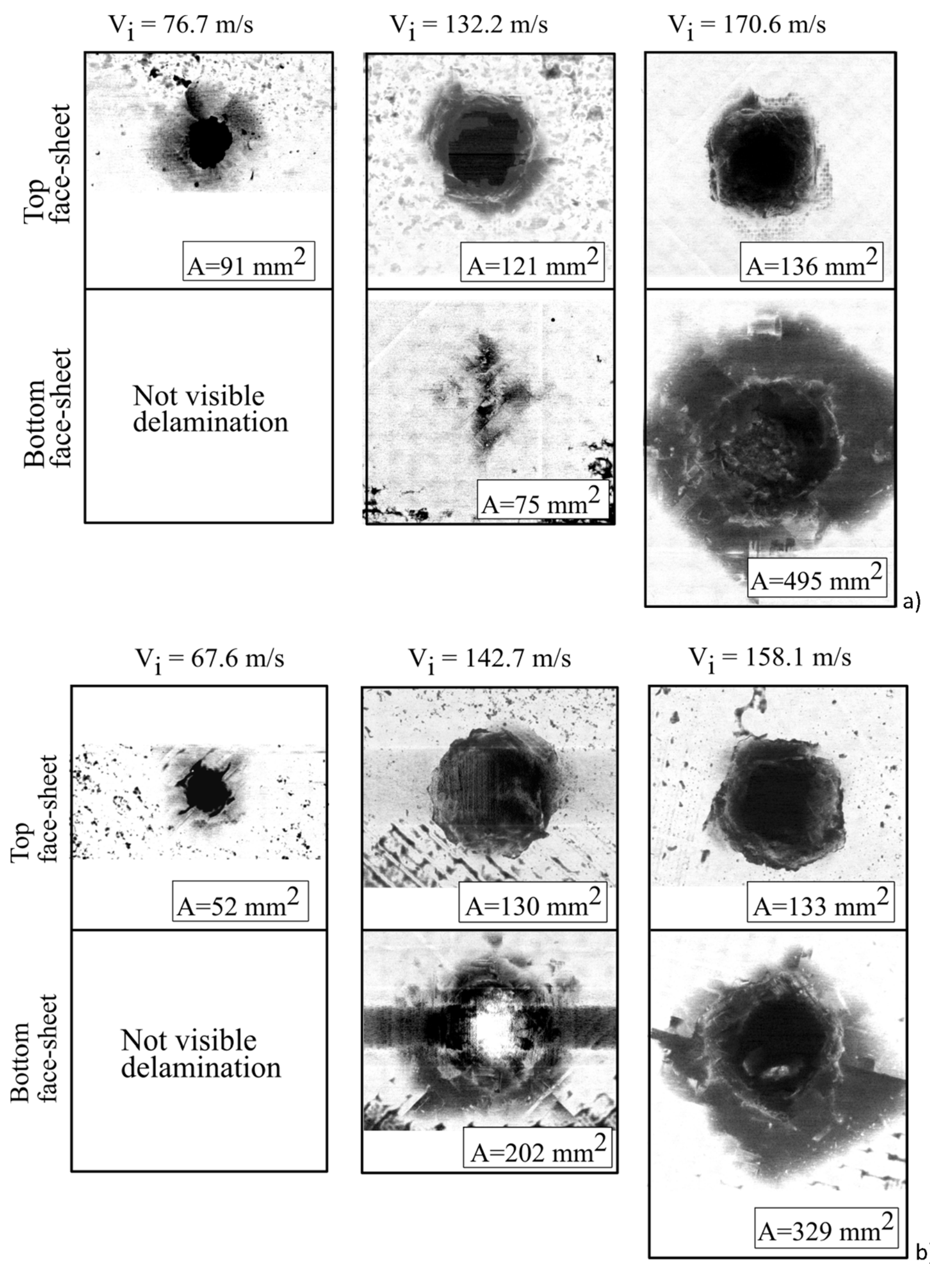

Fig. 14. Projected delamination area in front and back skins measured from X-ray tomography. a) Agglomerated cork core sandwich panels, b) PET foam core sandwich panels.

The phenomenon also appeared in the sandwich with PET core, tested for the middle impact velocity $V_i = 142.7$ m/s (Fig. 14b). By contrast, the damage in the back skin in the sandwich with agglomerated cork core at this velocity was smaller than in the front skin. At this impact velocity, the damaged area in the front skin was also slightly smaller (around 7 %) than in the other sandwich panels. This suggests that the adhesion between skin and core may be better in the sandwich panels with an agglomerated cork core.

4. Conclusions

In this work, the impact behaviour of sandwich panels with two different sustainable core materials (agglomerated cork and PET foam) and skins made of a CFRP laminate were studied experimentally. A 3D-DIC analysis was used to study the response of the panels during impact by measuring the out-of-plane displacement and in-plane strain fields. Furthermore, visual inspection and X-ray tomography were used to assess the damage and failure mechanisms in the sandwiches.

One of the first observations of this study suggests that for velocities below the perforation velocity, the core material seemed to have a minor role in the rebound energy ratio. The PET foam core seemed to provide slightly greater dissipation effects than its agglomerated cork counterpart.

The 3D-DIC results showed that the magnitude and shape of the front skin out-of-plane displacement were governed by the perforation process and the formation of a plug. In impacts with no perforation, the out-of-plane displacements were larger since the skin deflected together with the advancing projectile. However, when the front skin was perforated, a plug was formed which separated from the rest of the skin. Consequently, the area furthest away from the point of impact could not deform solidly with the advancing projectile. This reduced the overall out-of-plane displacement in the front skin.

The strength and stiffness of the core material also influenced the out-of-plane displacement of the front skin during impact. Panels with agglomerated cork core showed greater displacements than the stiffer PET foam core panels.

It was observed that during impact, a lobular-shaped strain distribution was formed around the impact region with maximum strains at the impact point and decreasing in the radial direction. Once penetration occurred and a plug formed, the skin was unable to transfer the load from the central region where the projectile made contact further out.

The study of post-impact damage and failure morphology suggested that the cross-shaped crater formed in the front skin during penetration is the product of a complex interaction of different phenomena such as early intra-laminar ply failure, delamination and large bending of broken plies. Subsequently, the deformed parts of the cross-shaped damage interact with the neighbouring core material and compress it laterally.

The formation of a very large fracture surface in the interface between the back skin and the core was also detected by visual and XCT inspection of sandwich panels with a PET foam core. It was observed that cracks propagated radially along the core and, in some cases, were accompanied by debonding.

Skin delamination is also another critical failure mechanism of the sandwich panels due to the large delamination areas measured and it occurred at moderate velocities. Nonetheless, this failure mechanism was not observed in sandwich panels with an agglomerated cork core, suggesting that the face sheet-core interface is stronger in these panels.

Delamination in the back skin was dominated by impact velocity and whether there the front skin was penetrated. If there was no penetration, the back skin suffered no delamination. By contrast, if the front skin was penetrated, delamination appeared in the back skin propagating further away than in the front skin, depending on the impact velocity. As a result, once penetration occurred, back skin delamination was a critical damage mechanism.

CRediT authorship contribution statement

Arturo Gomez: Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Sonia Sanchez-Saez:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition. **Enrique Barbero:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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