Residual bending behaviour of sandwich composites after impact

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Abstract
This work investigates the residual mechanical behaviour of composite sandwich panels in bending after impact loading conditions. The sandwich panels were made of an epoxy/glass face sheet with three different core materials: styrene acrylonitrile foam, polyethylene terephthalate foam and Balsa wood. A three-point bending test was performed in order to determine the reference stiffness. A low-velocity impact test and thereafter the three-point bending test were performed with the same specimens. The failure modes during bending tests were captured using a high-speed camera. It was found that multiple shear cracks with progressive failure were present in the core of styrene acrylonitrile and polyethylene terephthalate panels in bending after impact tests, whereas single shear crack with sudden failure was the case for Balsa panels. The initial bending stiffness decreased approximately 30.5, 35.2 and 55.6% for Balsa, styrene acrylonitrile and polyethylene terephthalate panels, respectively, in bending after impact tests due to the influence of the pre-damage from the low-velocity impact tests. The reduction in collapse force was also quantified for Balsa, styrene acrylonitrile and polyethylene terephthalate panels as 22.8, 4.9 and 22.1%, respectively.

Keywords
Residual strength, sandwich composite, low-velocity impact, bending, styrene acrylonitrile foam, polyethylene terephthalate foam, Balsa core, glass/epoxy

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Introduction

Sandwich composites consisting of thin fiber-reinforced polymer (FRP) skins and a thick low-density core have been used in load bearing structural designs due to their low weight and high strength to weight ratio. Some of the examples of sandwich composites are wind turbine blades, structural panels used in airplanes and truck trailers. The skins of a sandwich composite have the ability to carry the bending loads on the panel while the core, usually made of a honeycomb construction or a wood or a foam type, carries the shear loads and maintains the distance between the two face sheets. Typically, sandwich constructions have thin skins with a thicker core. In practical use, such products can suffer some impact loading during their lifetimes. These impacts have a negative influence on the residual stiffness and strength of these products. Therefore, the impact damage tolerance is an important parameter to be considered for sandwich panels used in load bearing applications and it is necessary to understand and describe the influence of an impact loading on the residual mechanical performance of the sandwich composite.

In literature, there have been several studies which investigated the impact behaviour of composite sandwich panels. The impact behaviour of sandwich composites with different cores e.g. polyvinyl chloride (PVC), cork and Balsa was investigated in Castilho et al. [1]. It was found that Balsa had the highest reaction force; on the other hand, cork had the best ability to absorb impact energy by deforming instead of breaking. The influence of core properties on the perforation resistance in composite sandwich panels was studied in Hassan and Cantwell [2]. A polyethylene terephthalate (PET) foam was compared with linear PVC and cross-linked PVC and it was found that the cross-linked PVC has the highest reaction force during impact. In Wang et al. [3], low-velocity impact (LVI) behaviour of foam-cored composite sandwich panels was studied. A relation between the skin thickness and the absorbed impact energy and the contact duration with the reaction force was found. It was found that as the skin thickness increased, the absorbed energy as well as the contact duration decreased, while the reaction force increased. It was also shown that the damage state and the impact response were independent of core thickness, which was tested with two different core thicknesses; 10 and 25 mm. The oblique impact response of sandwich composite having carbon/epoxy face sheets and Nomex honeycomb core was investigated in Iváñez et al. [4]. It was found that the peak load and energy absorption increased with increasing impact energy and impact angle, while the contact time remained almost constant. In Ahmed et al. [5], the damage mechanism of foam sandwich composites was investigated in a quasi-static and an LVI loading condition. High-velocity impact tests at 1000 m/s were conducted in Moon et al. [6] with various rear plate materials attached to a sandwich composite system. In Kursun et al. [7], the damage behaviour of aluminum sandwich composite plates subjected to an LVI loading was examined. The LVI analysis of three-dimensional woven hollow core sandwich composites consisting of woven E-glass fabric and epoxy vinyl ester
was conducted in Hosseini et al. [8] experimentally and numerically. The study presented in Yang et al. [9] investigated the effects of LVI energy and temperature on the damage mechanics of sandwich composite panels with carbon fiber/epoxy woven face sheets and PVC foam cores. The LVI of various sandwich composites was studied further in Wang et al. [10], Al-Shamary et al. [11], Nemes and Simmonds [12], Hazizan and Cantwell [13], Bhuiyan et al. [14], Dogan and Arikan [15], Wadley et al. [16], Mei et al. [17–19].

In addition to impact, there have been studies that deal with the compression-after-impact (CAI) behaviour of sandwich panels. The CAI of sandwich panels with damage confined to the face laminates has been extensively investigated in many research works [20–24]. In Shipsha and Zenkert [25], the CAI strength of composite sandwich panels with core crushing damage was studied. The experiments showed that there was an influence of an impact on the compression strength of a composite sandwich panel, albeit this reduction was not so significant. The CAI strength of honeycomb composite sandwich panels was studied in McQuigg et al. [26] and it was found that the residual compressive strength reduction was the highest in lightly damaged specimens, however, increasing the level of damage resulted in further reduction of the compression strength (with the reduction decreasing in magnitude). The response of a composite sandwich panel subject to an LVI and CAI was investigated in Zhang et al. [27]. The CAI strengths of the damaged coupons were found to reduce about 4–10 MPa compared to the intact specimens. A four-point bending (4PB) test was used in Nettles et al. [28] to investigate the CAI of sandwich composites. In Wang et al. [29], CAI behaviour of sandwich panels consisting of plain-weave laminated face sheets and polyurethane (PUR) foam core was studied. The non-uniform strain field during compression tests after impact was obtained using the digital image correlation technique. The static and dynamic behaviour of sandwich composite plates was analysed extensively in Phung-Van et al. [30–33] using numerical techniques such as isogeometric analysis and higher-order shear deformation theory [30, 31], cell-based smoothed discrete shear gap method [32] and edge-based smoothed stabilized discrete shear gap method [33].

Apart from CAI, there have been limited studies on the bending-after-impact (BAI) behaviour of sandwich panels which is one of the loading scenarios during the service life of the product. BAI was studied in Göttner et al. [34] and Klaus et al. [35] performing an LVI and subsequent 4PB tests. A strong dependency between the amount of damage and deformations caused by the impact energy and the bending strength of the damaged sample was found. PVC foam core sandwich panels with different face sheets (epoxy resin reinforced with E-glass, S-glass and carbon fibers) were studied in Özen [36]. A three-point bending (3PB) test was performed as post-impact loading in which the peak load, deflection at the peak load for impact tests, and the flexural strength during the 3PB were observed experimentally.

The effect of core material type on the residual bending and failure behaviour of sandwich panels has not been considered in the aforementioned literature where a
few core materials, i.e. aramid paper foldcore [34, 35] and PVC foam [36] were studied in BAI condition. Therefore, there is ample room for conducting research on the quantification of residual bending performance of sandwich composites in BAI conditions in order to have a better understanding of the damage tolerance of these structures. This paper thus aims to fill this gap by experimentally investigating the BAI behaviour of three different sandwich panels having commonly used foam cores, a styrene acrylonitrile (SAN) foam, PET foam and Balsa wood with epoxy/glass face sheets. The mechanical behaviour of sandwich panels is studied using 3PB test in which pre-damaged specimens subjected to an LVI are utilized for the considered core materials. In addition, the influence of core material type on the failure modes of the sandwich composites during BAI is also investigated using a high-speed camera. The BAI results are compared with the reference case in which the bending-only (BO) condition is applied to specimens without a pre-damage.

**Materials**

The composite face sheets were made of glass fibers with an epoxy resin. The following glass fibers were used for the face sheets with three layers of $[0^\circ/-45^\circ/90^\circ/45^\circ]$ lay-up:

\[ \text{Saertex S32EQ260-00820-01270-450000 Quadraxial-glass-fabric 822 g/m}^2 \text{ with polyether sulfone (PES) tricot-warp stitching} \]

This type of fabric is quadraxial which means it has four different fiber directions in a single ply. The fiber reinforcements are stitched together with a PES tricot-warp stitching. One single layer including the stitches has a weight of 822 g/m$^2$. An optical microscopy image for the face sheet is depicted in Figure 1.

Three different core materials were used for the core: Gurit Corecell M closed cell SAN foam with a density of 85 kg/m$^3$, Airex T90.60 closed cell PET foam with a density of 65 kg/m$^3$ and Baltek Sb.100 end grain balsa wood with a density of 155 kg/m$^3$. Optical microscopy images for the core materials are shown in Figure 2. These core materials were selected since they have been used in various load-bearing applications and investigated in recent studies in literature [1, 2, 37].

The sandwich panels were manufactured using the vacuum-assisted resin transfer moulding technique. Perforated cores were utilized which had sort of resin distribution channels in order to aid the resin flow during vacuum infusion. The sandwich panels were build-up in the mould with first three layers of quadraxial layers. The core was placed on top of the bottom skin and then again three layers of quadraxial fibers were placed on top of the core. After leaving the sandwich panel under vacuum for an hour, the resin was infused at 40°C. When the entire laminate was saturated with the epoxy resin, the temperature of the mould was increased to 80°C. The mould was kept at 80°C for 8 h to ensure a proper curing of the epoxy resin. The dimension of the produced panels was $400 \times 400$ mm with a nominal
thickness of 30.2 mm. The thickness of the face sheets was 2.4 mm and the core thickness was 25.4 mm.

**Experimental**

Two different mechanical tests were performed:

a. **BO tests:** The 3PB tests were performed according to ASTM C393/C393M as a reference case in order to have a baseline for the mechanical behaviour and failure modes during bending. The specimens were prepared by cutting the manufactured sandwich panels of $200 \times 75$ mm using a diamond saw.

b. **BAI tests:** In order to have a pre-damaged state in the sandwich panels, an LVI test was carried out for the undamaged sandwich panels having the same dimensions used in BO tests, i.e. $200 \times 75$ mm. A falling weight impact machine was utilized in LVI tests. Having been subjected to the impact, the residual bending stiffness, collapse force and failure modes of the sandwich panels were determined by performing 3PB tests.

Total of six specimens were tested in each BO and BAI experiments. In the following, the details of BO and BAI tests are explained.

**BO test**

A schematic view of the 3PB setup is shown in Figure 3. The 3PB test was performed according to testing standard ASTM C393/C393M on a Zwick Z100
tensile testing machine, capable of performing forces up to 100 kN. The dimensions of the loading cylinder and supports are shown in Figure 3. The specimens were subjected to a vertical displacement with a vertical speed of 6 mm/min which was employed until the reaction force dropped 50% or until the deformation reached 20 mm. The complete 3PB setup is depicted in Figure 4 (right). A high-speed camera was also attached to the 3PB setup to observe the failure modes of the specimens.

**BAI test**

The BAI specimens were the same size as in BO tests (see Figure 3). The specimens were first subjected to a falling weight of 5.895 kg from a height of 60 cm in the LVI tests. The velocity of the falling weight was 3.4 m/s when it hits the sandwich panel which corresponds to an impact energy level of 34.7 J. The test was performed using Dynatup, 8250 falling weight impact machine at room temperature. The specimens were impacted with a hemispherical tup of 16 mm diameter. The loading cell used in this test was a Kistler 901 1A SN1530440, capable of processing a 15 kN force. The impact tup was attached to an extension beam, in order to enable the impact on the panel on the sub-plateau of the machine. The extension beam was attached to the added weight of 4.95 kg. The complete falling weight (extension beam, bolts, tup, added weight), weighted 5.895 kg and the specimens were fixed with four clamps. After the impact took place, two pneumatic support units moved up to prevent a second impact of the impact tup after bouncing. The clamped sandwich panel to the impact machine is shown in Figure 4 (left). The impacted specimens were subsequently subjected to the quasi-static loading, i.e. 3PB, as in BO tests (see Figure 4 (right)).

During the LVI tests, the energy absorbed by the sandwich panels is calculated using the following expression [5, 38, 7, 27]

\[
E_a(t) = m\frac{v^2}{2} - \frac{v(t)^2}{2}
\]
Figure 3. Schematic view of the BO (3PB) and LVI test setup with dimensions. BO: bending-only; LVI: low-velocity impact; 3PB: three-point bending.

Figure 4. Illustration of the BAI test sequence with the experimental setup used for the LVI tests (left) and BO tests (right). BAI: bending-after-impact; BO: bending-only; LVI: low-velocity impact; 3PB: three-point bending.
where $m$ is the falling weight, $v_0$ is the initial impact velocity, $v(t)$ is the impactor velocity at time $t$ which can be calculated as

$$v(t) = v_0 - \int_0^t \frac{F(t)}{m} dt$$

where $F(t)$ is the force measured at time $t$.

**Results and discussion**

**BO**

The force-displacement curves for the SAN, PET and Balsa core sandwich panels are depicted in Figure 5. The initial linear slope in the force-displacement diagrams indicates the bending stiffness of the sandwich panels [11]. The mean of the bending stiffness values for Balsa, SAN and PET cored panels were found to be approximately 4029, 1963 and 771 N/mm, respectively. It is seen that the balsa panel has the highest bending stiffness and PET has the lowest as expected according to their mechanical properties. The mean of the peak force or the collapse force was approximately 10813, 4735 and, 2524 N for Balsa, SAN and PET, respectively. Balsa panel can bare up approximately twice as much force as the SAN foam and approximately four times the force of the PET foam panels. The force-drop after the peak force cannot be seen in the force-displacement diagrams when the drop was higher than 50% because this force-drop stopped the test and therefore there

![Figure 5. Force-displacement diagrams from BO tests.](image)

BO: bending-only; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
were no data available after the force-drop. After certain deformation of the panels, a plastic deformation took place for SAN and PET foam panels which can be seen in Figure 5. The severity of the plastic deformation was found to be the highest in PET sandwich panel and the lowest in Balsa sandwich panel. This indicates that the Balsa sandwich panel is more brittle than PET and SAN panels. A sudden failure (force drop) was observed for most of the specimens except BAL4 (fourth Balsa sample) and PET4 (fourth PET sample) as shown in Figure 5. First, the core failed in shear mode and subsequently the crack propagated towards core-skin interface and simultaneously caused debonding of skin from the core. This failure behaviour is shown in Figure 6. PET4 specimen failed in indentation mode as seen in Figure 7, i.e. the core was compressed instead of sheared apart. The corresponding force-displacement response is seen in Figure 5 where PET4 specimen has a high degree of displacement with plastic deformation without a drop in the force more than 50%. Similarly, BAL4

![Figure 6](image_url)

**Figure 6.** Core shear failure followed by core-skin delamination observed from BO tests for (a) SAN specimens, (b) PET specimens and (c) Balsa specimens.

BO: bending-only; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
specimen had also a high degree of displacement which was caused by the core-skin debonding after core shearing followed by the mechanical jamming in the core as seen in Figure 8.

**Low-velocity impact**

Undamaged sandwich panels were subjected to LVI with the impact level of 34.7 J. The load-displacement curves of Balsa, SAN and PET panels are given in Figures 9–11, respectively. It can be concluded that the balsa sandwich panel was the
strongest panel as expected since the first peak load (the load to penetrate the upper skin) was highest for the balsa panels. The maximum penetration depth of the indensor was obtained from the maximum displacement values from Figures 9-11. The mean of the maximum penetration depth of the specimens

Figure 9. Force-displacement diagrams for Balsa panels after the LVI. LVI: low-velocity impact.

Figure 10. Force-displacement diagrams for SAN panels after the LVI. LVI: low-velocity impact; SAN: styrene acrylonitrile.
was obtained as 6.36, 7.88 and 12.65 mm for Balsa, SAN and PET cored sandwich panels, respectively. At each specimen, the face sheet was failed first at the peak force. Subsequently, there was a gradual decrease in force at which the core was plastically deformed and failed due to penetration of the indentor. The plastic deformation after impact was more dominant in PET foam core panels.

The evolution of the absorbed energy calculated by equation 1 is depicted in Figure 12(left). It is seen that the absorbed energy gets maximum at approximately 3, 4 and 7 ms for Balsa, SAN and PET panels, respectively. The absorbed energy decreased after the maximum values due to the rebounding phenomena took place

![Graph](image1.png)

**Figure 11.** Force-displacement diagrams for PET panels after the LVI. LVI: low-velocity impact; PET: polyethylene terephthalate.

![Graph](image2.png)

**Figure 12.** Evolution of the absorbed energy (left) and corresponding mean and standard deviation of absorbed energy at the end of LVI tests (right). LVI: low-velocity impact; BAL: Balsa; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
governed by the internal elastic energy [7]. The absorbed energy at the end of LVI tests is depicted in Figure 12(right). It is seen that mean absorbed energy level was approximately 29.6, 28.7 and 29.9 J for Balsa, SAN and PET panels, respectively. Although the peak force during LVI tests was the lowest for PET panels, the energy absorbed by PET panels was approximately the same as Balsa panels and higher than SAN panels due to the fact that there was more plastic deformation in the PET core.

Examining the panels after the impact tests, it can be seen that all panels had visible damage as seen in Figure 13. The PET foam core sandwich panels had the least visible damage and the SAN and Balsa panel had approximately the same amount of visible damage. This can be explained by the lower reaction force of the PET sandwich beam due to lower stiffness of the PET material which created less internal stress to break the glass/epoxy skin as compared with the SAN and Balsa sandwich beams. The PET foam absorbs the energy by plastically deforming instead of breaking like the Balsa wood which can be seen in Figures 9-11, i.e. the PET sandwich panels have much more deformation than the Balsa specimens and the SAN specimens. The failure of the skin was found to be similar for all pre-damaged specimens such that there were fiber breakage and matrix cracking.

**BAI**

In BAI tests, the damaged panels due to LVI were subjected to 3PB test. The force-displacement diagrams obtained from BAI together with BO are presented in Figures 14–16 for Balsa, SAN and PET sandwich panels, respectively. It is seen

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**Figure 13.** Images of SAN, PET and Balsa sandwich beams subjected to the LVI with 34.7 J. LVI: low-velocity impact; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
that the initial bending stiffness which is defined as the first linear slope in the force-displacement diagrams reduced. The mean and standard deviation values of the initial bending stiffness from BO and BAI tests are depicted in Figure 17. The reduction in bending stiffness was found to be approximately 30.5, 35.2 and 55.6%.

**Figure 14.** Force-displacement diagrams of Balsa panels for BO and BAI tests. BAI: bending-after-impact; BO: bending-only.

**Figure 15.** Force-displacement diagrams of SAN panels for BO and BAI tests. BAI: bending-after-impact; BO: bending-only; SAN: styrene acrylonitrile.
Figure 16. Force-displacement diagrams of PET panels for BO and BAI tests. BAI: bending-after-impact; BO: bending-only; PET: polyethylene terephthalate.

Figure 17. Comparison of the bending stiffness of sandwich panels (Balsa (BAL), SAN and PET sandwich panels) obtained from BO and BAI tests. The bar diagrams show the mean value and the error bars show the standard deviation. BAI: bending-after-impact; BO: bending-only; BAL: Balsa; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
for Balsa, SAN and PET panels, respectively. This indicates that the LVI of PET sandwich panels has a more significant effect on the residual bending stiffness as compared with SAN and Balsa sandwich panels. The failure mechanism of Balsa panels in BAI tests was found to be similar as in BO tests, i.e. sudden force drop with a single core shear failure followed by a core-skin delamination. On the other hand, the failure mechanism significantly changed for SAN and PET panels in BAI tests: a progressive failure was the case in which multiple cracks occurred until the force drops by 50% or maximum deflection reaches 20 mm. To illustrate, the damage evolution for the fifth PET sandwich panel during BAI tests taken by the high-speed camera is depicted in Figure 18 in which the development of multiple microcracks is indicated by the arrows. The pictures of the failure modes at the end of BAI tests are shown in Figure 19. The cause of the multiple cracks in the PET and SAN cores is the damage accumulated in the core after the LVI tests.

![Figure 18. Damage evolution for the fifth PET sandwich panel during BAI tests. Arrows indicate the location of internal cracks during damage evolution. BAI: bending-after-impact; PET: polyethylene terephthalate.](image-url)
As a result of the progressive failure, the displacement values at the collapse in BAI tests were found to be higher than the ones in BO for SAN and PET foam panels. The collapse force, which is the maximum force in the force-displacement diagrams, was found to be lower in BAI tests as compared with BO tests. The collapse force in BO and BAI tests for Balsa, SAN and PET sandwich panels is compared in Figure 20. It is seen that the collapse force reduced approximately 22.8, 4.9 and 22.1% for Balsa, SAN and PET panels, respectively. The standard deviation of collapse force was the highest for Balsa panels and lowest for PET panels. As a result of the progressive failure, the reduction in collapse force in percentage was higher for Balsa panels as compared with SAN and PET panels.

Figure 19. Failure modes of sandwich panels during BAI tests. Multiple shear cracks in the core and subsequent progressive skin-core delamination for (a) SAN and (b) PET panels. Single shear crack and subsequent abrupt core-skin delamination for (c) Balsa panel. BAI: bending-after-impact; PET: polyethylene terephthalate; SAN: styrene acrylonitrile.
Conclusions

The mechanical behaviour of composite sandwich panels was experimentally investigated in bending (BO), impact (LVI) and bending after impact (BAI) in the present work. The residual mechanical performance of sandwich composites with SAN foam, PET foam and Balsa core with (quadrax) glass/epoxy face sheets was quantified. The damage initiation and progression during bending tests were captured using a high-speed camera. The damage zones in the core and face sheets were examined critically.

The residual bending performance of sandwich panels was significantly influenced by the LVI (with an impact energy of 34.7 J) although the absorbed energy levels of the panels (~30 J) were found to be approximately the same as seen in Figure 12. The failure mode of SAN and PET panels changed in BAI, however, this was not the case for Balsa panels. Multiple shear cracks with progressive failure were found to present in the core of SAN and PET panels in BAI tests, whereas single shear crack with sudden failure was the case for Balsa panels in BAI tests. On the other hand, sudden failure with single shear crack was present in the BO tests for Balsa, SAN and PET panels. The shear cracks in the core of the panels propagated towards the core-skin interface and caused a delamination during both BO and BAI tests. The initial bending stiffness decreased approximately 30.5, 35.2 and 55.6% for Balsa, SAN and PET panels, respectively, in BAI tests as seen in Figure 17 due to the influence of LVI damage. The reduction in collapse force was also quantified as 22.8, 4.9 and 22.1% for Balsa, SAN and PET panels,
respectively, as shown in Figure 20. As a result of the progressive failure, the displacement values at collapse in BAI tests were found to be higher than the ones in BO for SAN and PET foam panels.

In order to further develop damage tolerant sandwich composites and to have a deeper understanding of the influence of an impact loading on the residual mechanical performance, the BAI behaviour also has to be investigated further by performing numerical analyses with dedicated material models for damage initiation and progression.

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