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Experimental study of the indentation of sandwich panels with carbon fibre-reinforced polymer face sheets and polymeric foam core

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Abstract: This paper presents experimental studies on the quasi-static indentation of a rigid indenter into sandwich panels with carbon fibre-reinforced polymer face and polymeric foam core. It was found that both nose shape and foam core density have large influence on the indentation response of the sandwich panels in terms of absorbed energy, indentation at failure and damage area. A dependency of the indentation load on the supporting condition was observed. It was also found that the difference in indentation resistance between the sandwich panel and its corresponding core material depends on the core density.

Key words: A. Layered structures; D. Mechanical testing; Indenter nose shape

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1 INTRODUCTION

The use of sandwich structures is becoming increasingly popular in aerospace and marine industries and other areas where lightweight materials with high in-plane and flexural stiffness are needed [1]. Sandwich structures are prone to impact threats from a wide range of projectile shapes, sizes and velocities during service and maintenance life. Low velocity impacts are considered as the most dangerous situations because of the difficulties to detect the damages. After an impact, a large reduction in the mechanical performance may occur [2]. Thus, a good understanding of indentation and impact response is necessary in order to predict and assess their residual strengths.

Although damage and permanent deformations of sandwich structures normally occur during impact by foreign objects, quasi-static indentation has been widely used to represent and understand the impact response because strain-rate and wave propagation effects are commonly negligible for the low velocity impacts [2, 3]. A preliminary research in the quasi-static indentation and low velocity impact of sandwich panels with poly-methacrylimide (PMI) foam core and carbon woven fabric face sheets using a variety of impactors was performed by Flores-Johnson [4]. It was found that the resistance forces of the sandwich panels were very similar in both quasi-static indentation and low velocity impact indicating that quasi-static indentation can be used to study low velocity impact responses.

Quasi-static indentation and low velocity impact of sandwich panels and beams have been widely studied by several authors. Lolive and Berthelot [5] studied the quasi-static indentation of sandwich panels with poly- vinyl chloride (PVC) core with two densities and E-glass laminate face sheets using cylindrical indenters with different diameters. It was found that the indentation load increases with the increase of the density of the core and the load is increased when the diameter of the indenter increases.

Low velocity impact on sandwich panels and sandwich beams with PMI foam core and carbon fibre-reinforced polymer (CFRP) face sheets using hemi-spherical and cylindrical impactors has been studied by Sun and Wu [6, 7]. They identified several failures modes, i.e., matrix cracking of the face sheet, skin/core debonding and core crushing. Rizov et al. [8] studied low velocity impact on sandwich panels with PMI foam core where panels with glass fibre-reinforced polymer (GFRP) face sheets were indented quasi-statically by hemi-spherical indenter. It was observed that the load-indentation curve showed a linear behaviour for low values of indentation, followed by a non-linear regime with a quick decrease in the sandwich panel stiffness caused by the extensive foam core crushing in the area under the indenter.

Indenter nose shape has great influence on the indentation and impact resistance of sandwich panels, which has been shown, for example, in Wen et al. [9] where quasi-static indentation into sandwich panels with PVC foam core and GFRP face sheets was studied using hemi-spherical, flat and conical indenters. Zhou et al. [10] investigated the quasi-static indentation of sandwich panels with aluminium honeycomb core and CFRP face sheets using hemi-spherical and flat indenters, and showed that the failure mechanisms depend on the indenter nose shape.

Most investigations about the effect of the nose shape on the quasi-static response of sandwich panels were limited to flat and hemi-spherical indenters. In this work, a complete experimental data on the quasi-static indentation behaviour of sandwich panels with different PMI cores are reported systematically for a variety of indenter nose shapes (conical, conical-truncated, flat, hemi-spherical). The bending of the sandwich panels under localised load is discussed. The influence of the density of the core on the indentation and penetration behaviours is also studied. The ultrasonic C-scan technique is used to show the post-indentation damage of the sandwich panels. A comparison of the sandwich structural behaviour with its corresponding core material behaviour is also presented. Section 2 describes the materials and their mechanical properties. The experimental details are given in Section 3. The experimental results are presented in Section 4. Finally, a discussion of the results is presented in Section 5 followed by conclusions.

2 MATERIALS

2.1 Sandwich panels

Sandwich panels consist of a PMI (trade name Rohacell [11]) foam cores and two carbon fibre woven fabric lamina face sheets. Sandwich panels were supplied by Evonik Röhm GmbH, the manufacturer of the Rohacell foam core. Woven fabric lamina face is made of 0°/90° lay-up of Toho Tenax carbon fibre HTA plain weave fabric 5131 and epoxy resin (Bakelite EPR 04908 and EPH 04908). The total thickness of each woven fabric lamina face is 0.41 mm. The overall dimension of the sandwich panel is 100×100mm with 10.82 mm thickness. The faces were bonded to the core with an epoxy resin adhesive.

2.2 Foam cores

A range of Rohacell foam cores were used, which includes Rohacell 51WF, Rohacell 51RIMA, Rohacell 71WF, Rohacell 110WF and Rohacell 200WF with 10mm thickness.

The properties of the Rohacell foam cores from the manufacturer are summarized in Table 1 [11]. Although the mechanical properties of 51WF and 51RIMA appear to be the same, there is a difference in their resin absorption. There is virtually zero absorption for the 51RIMA compared to 51WF [11]. The mechanical properties of Rohacell 51WF and Rohacell 110WF foams have been studied by Li et al. [12] and Flores-Johnson et al. [13].

2.3 Mechanical properties of woven fabric face sheets

Uniaxial tensile tests were carried out in accordance to BS EN ISO 527:1997 [14] on rectangular specimens with 25 mm width and 110.5 mm gauge length using a standard 200 kN servo-hydraulic INSTRON testing machine with a cross-head speed of 0.5 mm/min. Axial and transverse strains were measured by strain gauges. Typical stress-strain curves from the experiment are shown in Fig.1. It can be seen that there is a decrease of stiffness at approximately 0.004 of strain. This is due to the failure of warp, fill yarns or matrix [15] which was visible during the experiment. At 0.031 of strain approximately, ultimate tensile strain was reached with a sudden transverse failure of the specimen.

Table 2 shows the mechanical properties obtained from Fig.1 and strain gauge measurements which includes Young's moduli E_{11} and E_{22} , Poisson's ratio ν_{12} , tensile strengths σ_{1T} and σ_{2T} , failure stresses σ_{1F} and σ_{2F} and failure strains ε_{1F} and ε_{2F} . The mechanical properties of the woven fabric face sheets are assumed to be transversely isotropic (Table 2).

3 EXPERIMENTAL

Quasi-static indentation tests were carried out for the sandwich panels described in Section 2.1 using a variety of indenters with different nose shapes (conical: indenters #1 and #2; truncated: indenter #3; flat: indenter #4 and hemi-spherical: indenters #5, #6 and #7, see Table 3). The indenters were mounted in a standard 200 kN INSTRON servo-hydraulic testing machine and the load was applied at a nominal strain rate of $1.54 \times 10^{-3} \text{ s}^{-1}$ at room temperature (22°C) and relative humidity of 27%. Tests were carried out to a maximum penetration of 9 mm.

Bending effect was also analysed using two different supporting plates (solid and framed). The framed supporting plate has a window of 80×120 mm to allow bending of the specimen during indentation. The specimen is held firmly using a clamping fixture assembly.

When solid plate was used for testing, specimens are only placed on the plate without any clamping device.

Post-indentation inspection of specimens to assess the damage area was carried out using a Through Transmission Inspection (TTI) ultrasonic C-scan method. A floor-standing jet probe inspection system manufactured by Midas-NDT LTD [16] was used. All C-scan images were captured using a 1 MHz probe and rectangular scanning of 50 mm/s.

4 RESULTS

4.1 Effect of the indenter nose shape

Figure 2 shows force-indentation curves for Rohacell 51WF foam cored sandwich panels using various indenters. It was observed that indentation resistance depends on the geometry of the indenter. The highest penetration resistance was observed for the flat indenter (#4) in contrast with quasi-static indentation of Rohacell 51WF foam [17] where flat indenter gives the lowest penetration load. This can be explained by the fact that, in quasi-static indentation load of the foam, the penetration resistance is localized while, in quasi-static indentation of the sandwich panel, the flat indenter bends the top face sheet more than other indenters causing a larger crushed area of foam, and thus, higher resistance. Several modes of face failure were identified in the indentation of sandwich panels. For indenters #1 and #2 with sharper nose, an initial perforation of the face without considerable crushing of the core was observed followed by the formation of a cruciform crack aligned along the fibre directions, which grows steadily with the increase of indentation (Fig. 3a). This type of failure has also been observed in glass fibre sandwich panels [9]. For indenters #3 and #4, after large deformation of the face, total or partial penetration through the thickness of the face (shear plugging, Fig. 3b) happened suddenly. For indenter #6, initial formation of a cruciform crack was observed followed by a sudden failure of the face after certain indentation (Fig. 3c).

Figure 4(a-e) shows C-scan images of the indented specimens corresponding to Fig.2. As expected, the damaged area (central black zone) depends on the nose shape of the indenter. The largest damaged areas are observed for indenters #3 and 4 while the smallest damaged areas are observed for indenters #1 and 2. It can also be observed that the damaged area shows some preferential orientation. For indenters #3, 4 and 6, the damaged area has a rhomboidal shape accompanied by fibre breakage, which is commonly observed for woven laminate faces [18]. In contrast, for indenters #1 and 2 the damaged area appears to be quasi-circular. In Fig.4(d), a black zone in the lower part below the central area can be observed

which is related to the skin/core debonding due to large bending deformation loaded by a flat indenter (Fig.3d).

It is noticed in Fig.2 that the diameter of the indenter nose has little influence on the stiffness of the sandwich panels. However, the diameter has a large influence on the ultimate failure of the face. This can be explained by the fact that the indenter with the largest diameter has larger radius of curvature, which reduces the local deformation of the face and allows more penetration of the indenter without causing the failure of the face. However, the damaged area was proportional to the diameter of the indenter.

4.2 Effect of the supporting plate

Figure 5 shows typical force-indentation curves of Rohacell 51WF foam cored sandwich panels using two different supporting plates, i.e. solid and framed supporting plates (SSP and FSP) for different indenters. Considerable differences in the force-indentation curves between the results for SSP and FSP were observed for indenters #3, 4 and 6, which can be explained by the fact that the FSP window allows more bending deformation, and thus, reduces the indentation resistance. The largest difference is observed for indenter #4 since there is a larger contact area between the indenter and the face leading to a larger bending of the panel before the failure of the face. The supporting condition has little influence on the force-indentation curve for indenters #1 and 2, which means that the effect of supporting condition on the force-indentation curve depends on the indentation contact area.

Figure 4(f-j) shows C-scan images of the specimens after indentation on FSP. As expected, the damage area (central black zone) is smaller for FSP test confirming that the global bending of panels reduces the localised damage. In Fig.4(j), a black zone (damaged area) along the length of the specimen can be observed. This is due to a large crack along the specimen (Fig.3e) caused by the large bending of the panel. These findings suggest that the location of constraints for a sandwich panel may have a strong effect on the in-service performance of the panel. This implies that the panel may be more vulnerable if it is not properly constrained.

4.3 Effect of the density of the core

Due to the limitation of specimens, only indenters #4 and 6 and SSP were used to study the effect of the core density. Figures 6(a) and 6(b) show force-indentation curves using indenter #4 and 6, respectively. Two general observations can be made from Fig.6, i.e., (i) for

the same indentation displacement, the indentation resistance increases with the increase of the foam density; (ii) the indentation displacement, at which failure occurs, decreases with the increase of the foam density. The first observation can be explained by the fact that the stiffness of the sandwich panel increases with the increase of the density of the core [19]. The second observation is due to the fact that the increase of stiffness due to the increase of density allows less deformation/bending of the face leading to a local stress concentration, and thus, the failure of the face.

Figure 7 shows C-scan images corresponding to Fig.6. C-scan images confirm observations from the curves. Damaged area decreases with the increase of density since the effect of the indentation becomes local due to the increase of stiffness of the panel. A large black area can be observed in Fig.7(b), in which the specimen was failed by skin/core debonding mechanism. It was also noticed that this failure mechanism happened several times for Rohacell 51RIMA suggesting that the low absorption of the resin [11] does not allow the formation of a good bonding interface between the foam and the face during the curing of the adhesive. This can be seen in Fig.8. For Rohacell 51WF the skin/core debonding also causes core failure but for Rohacell 51RIMA the core has very little damage.

5 DISCUSSION

Figure 9 shows a comparison of absorbed energies and indentations at failure corresponding to experiments shown in Fig. 6 for indenter #4 (flat) and #6 (hemi-spherical) and various core densities. Damage area is also compared in Fig. 9, which was obtained from C-scan images in Fig. 7. It can be seen that damage area decreases with the decrease of core density. This is explained by the fact that the damage is more localised for sandwich panels with greater core density due to the increase of stiffness. A slight larger damage area is observed for indenter #4 when compared with indenter #6; however, this difference is not significant. It is also observed in Fig. 9 that indentation at failure decreases when the core density increases which may be also attributed to the increase of stiffness of the panels, which allows less bending of the top face.

Figure 9 also indicates that the absorbed energy at failure depends on the core density; there is an increase of absorbed energy when the core density is increased from 52 to 75 kg/m^3 ; however, when the density is increased from 75 to 110 kg/m^3 , there is a reduction in the absorbed energy of the structure. This behaviour is observed for both indenters.

Figure 10 shows force-indentation curves of sandwich panels and their corresponding core materials for a variety of core densities and indenters #4 and 6. Force-indentation curves

of Rohacell 51WF and 110WF cores were taken from [17]. For Rohacell 71WF and 200WF cores, the curves were calculated using the analytical model developed in Flores-Johnson and Li [17]. It can be seen that the difference between indentation resistance of sandwich and that of the core material depends on the core density and the indenter nose shape. For indenter #6 (hemi-spherical) the difference between their indentation resistances decreases with the increase of core density. It can be observed that for Rohacell 200WF this difference is not significant, which implies that the indentation resistance of the sandwich is mainly contributed from the indentation resistance of the core material.

For indenter #4 (flat), the difference in indentation resistance between sandwich and core material is more noticeable than that observed when indenter #6 was used. This can be explained by the fact that the bending of the top face is larger when indenter #4 is used.

It is also noticed that after the top face fails, the resistance force of the sandwich panel is very similar to that of the core material for Rohacell 110WF and 200WF showing that the main contribution to the structural performance of the sandwich panel comes from the core.

The aforementioned observations are important from a design point of view since the use of a stiffer core in a sandwich structure not necessarily means that the sandwich panel will have a superior performance against indentation or low velocity impact when compared with more flexible core materials. Baral et al [20] observed that there is a limit in the improvement of performance of sandwich panels with honeycomb core against low velocity impact when the core density is increased. They found that the increase of core density leads to an increase of the flexural rigidity resulting in lower deflection of the structure, and thus, less energy absorption at first damage. This suggests that parametric studies should be carried out when using a sandwich structure for a specific application to obtain the optimum sandwich panel design.

6 CONCLUSIONS

Quasi-static indentation tests were carried out for a range of PMI foam cored sandwich panels using a variety of indenters with different nose shapes. It was found that both nose shape and foam core density have large influence on the indentation response of the sandwich panels. Several failure modes for the studied sandwich panels were identified including face failure, core failure and skin/core debonding. It was also found that the diameter of hemi-spherical indenters has little influence on the stiffness response of the sandwich panels but it has influence in the ultimate failure of the face sheet.

C-scan images showed that damaged area depends strongly on the indenter nose shape and foam core density. The largest damaged areas were observed for flat and truncated indenters while the smallest damaged areas were observed for conical indenters.

It was observed that the indentation load depends on the supporting plate of the sandwich panels. Framed supporting plate allowed bending of the sandwich panels leading to a decrease of the indentation resistance and a decrease of the localised damage. However, the supporting plate has little influence when conical indenters are used.

It was noticed that the difference in indentation resistances between sandwich panel and its corresponding core material depends on the core density. It was observed that for high density cores (Rohacell 200WF), the indentation resistances of both sandwich and core material were similar.

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TABLE CAPTIONS

Table 1 Mechanical properties of Rohacell foam cores [11]

Table 2 Tensile properties of carbon woven composite face sheet

Table 3 Indenter geometries

FIGURE CAPTIONS

Figure 1 Typical tensile stress-strain curves for CFRP woven fabric specimens

Figure 2 Typical force-indentation curves for Rohacell 51WF foam cored sandwich panels using different indenters.

Figure 3 Failure modes observed during indentation: failure of face: a) cruciform shape, b) shear plugging, c) cruciform shape plus fracture of fibres; d) skin/core debonding, e) fracture of the face, f) core shear

Figure 4 C-scan images of indented Rohacell 51WF cored sandwich panels using solid supporting plate: a) indenter #1, b) indenter #2, c) indenter #3, d) indenter #4, e) indenter #6; using framed supporting plate: f) indenter #1, g) indenter #2, h) indenter #3, i) indenter #4, j) indenter #6

Figure 5 Force-indentation curves for solid and framed supporting plates and different indenters with Rohacell 51WF foam cored sandwich panels

Figure 6 Force-indentation curves using a) indenter #4 and b) indenter #6 for sandwich panels with a variety of Rohacell foam cores

Figure 7 C-scan images of indented sandwich panels using indenter #4: a) 51WF, b) 51 RIMA, c) 71WF, d) 110WF, e) 200WF; using indenter #6: f) 51WF, g) 51 RIMA, h) 71WF, i) 110WF, j) 200WF

Figure 8 Failure by skin/core debonding: a) Rohacell 51WF, b) Rohacell 51RIMA

Figure 9 Absorbed energy and indentation at failure and damage area for sandwich panels with a variety of Rohacell foam cores and indenters #4 and 6

Figure 10 Force-indentation curves using indenters #4 and 6 for sandwich panels and their corresponding core materials: a) Rohacell 51WF, b) Rohacell 71WF, c) Rohacell 110WF and d) Rohacell 200WF

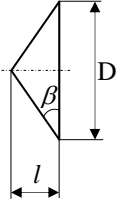
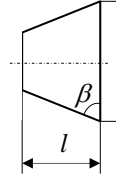
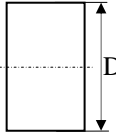
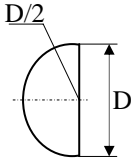
Table 1 Mechanical properties of Rohacell foam cores [11]

Properties	51WF	51RIMA	71WF	110WF	200WF
Density (kg/m ³)	52	52	75	110	205
Compressive strength (MPa)	0.8	0.8	1.7	3.6	9
Tensile strength (MPa)	1.6	1.6	2.2	3.7	6.8
Flexural strength (MPa)	1.6	1.6	2.9	5.2	12
Shear strength (MPa)	0.8	0.8	1.3	2.4	5
Elastic modulus (MPa)	75	75	105	180	350
Shear modulus (MPa)	24	24	42	70	150
Elongation at break (%)	3	3	3	3	3.5

Table 2 Tensile properties of carbon woven composite face sheet

E_{11} (GPa)	E_{22} (GPa)	ν_{12}	σ_{1T} (MPa)	σ_{2T} (MPa)	σ_{1F} (MPa)	σ_{2F} (MPa)	ϵ_{1F}	ϵ_{2F}
33.38	33.38	0.051	124	124	684	684	0.031	0.031

Table 3 Indenter geometries

Indenter #	Nose Geometry	Type	D (mm)	l (mm)	β (°)
1		Conical	20	10	45
2		Truncated	20	18	74.5
4		Flat	20	-	-
5		Hemi-spherical	16	-	-
6			20	-	-
7			25	-	-

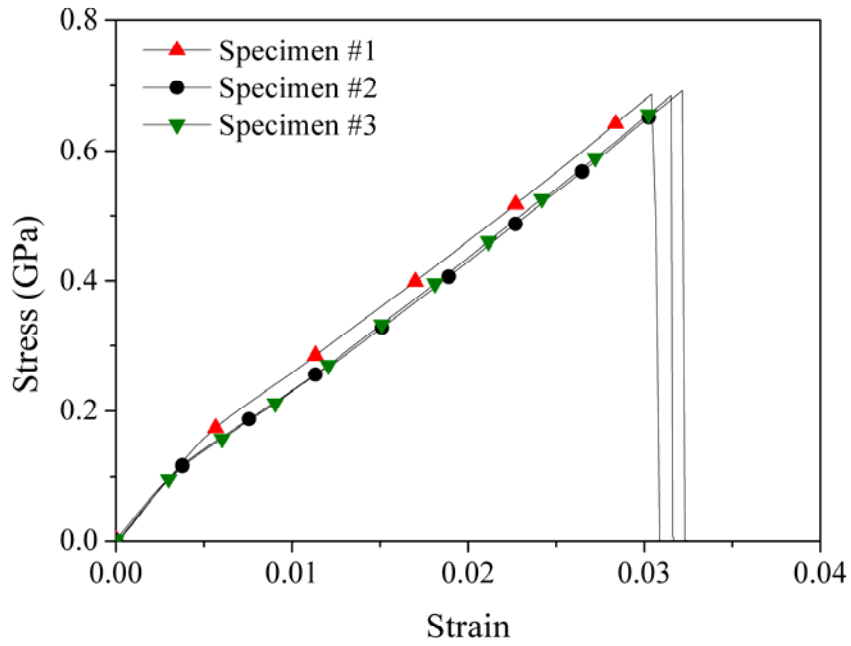


Figure 1 Typical tensile stress-strain curves for CFRP woven fabric specimens

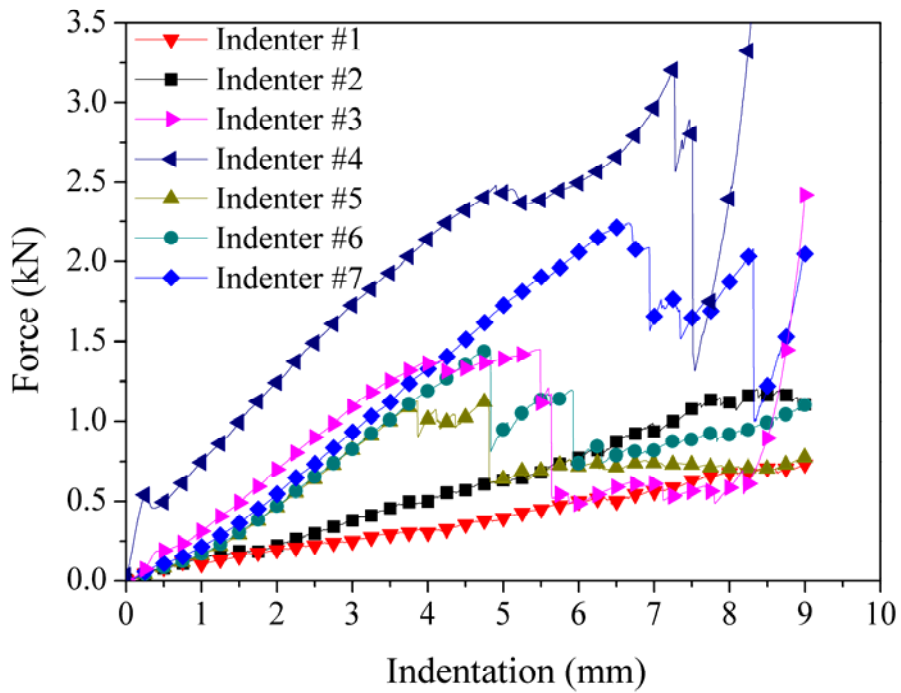


Figure 2 Typical force-indentation curves for Rohacell 51WF foam cored sandwich panels using different indenters.

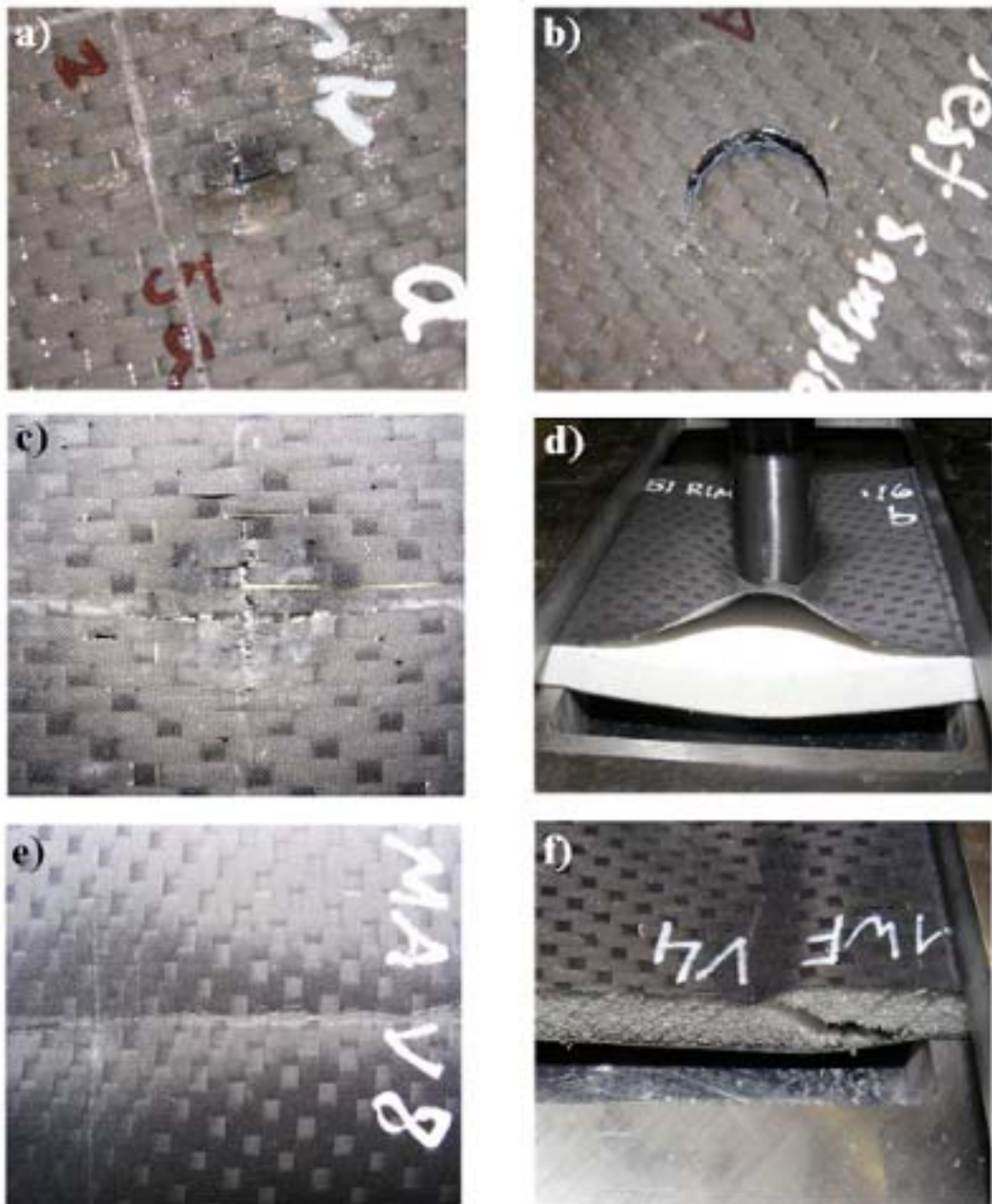


Figure 3 Failure modes observed during indentation: failure of face: a) cruciform shape, b) shear plugging, c) cruciform shape plus fracture of fibres; d) skin/core debonding, e) fracture of the face, f) core shear

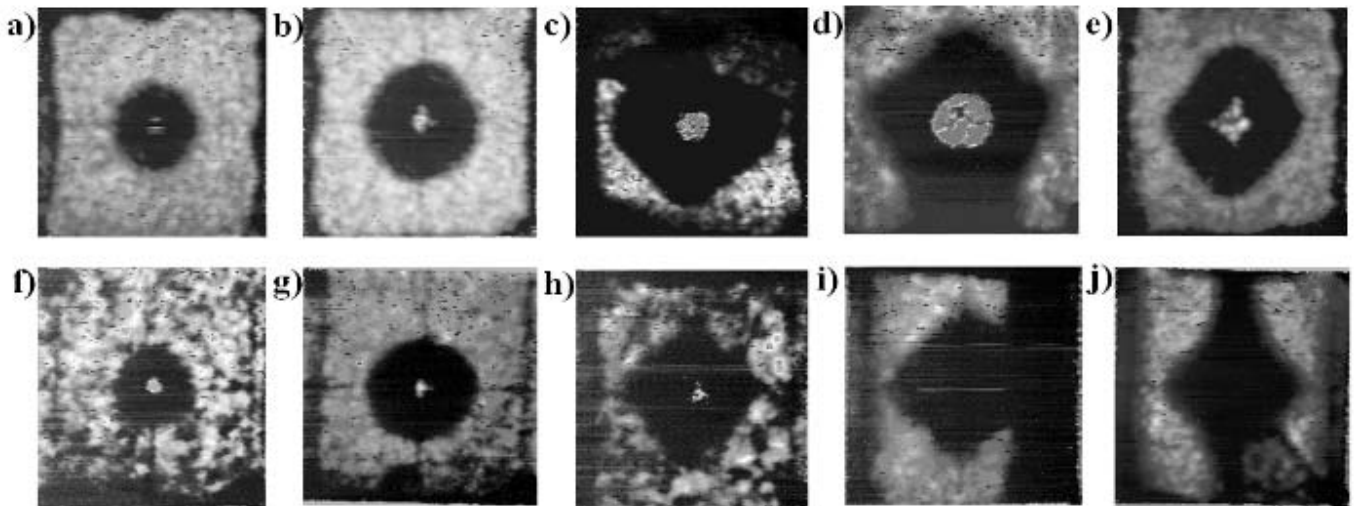


Figure 4 C-scan images of indented Rohacell 51WF cored sandwich panels using solid supporting plate: a) indenter #1, b) indenter #2, c) indenter #3, d) indenter #4, e) indenter #6; using framed supporting plate: f) indenter #1, g) indenter #2, h) indenter #3, i) indenter #4, j) indenter #6

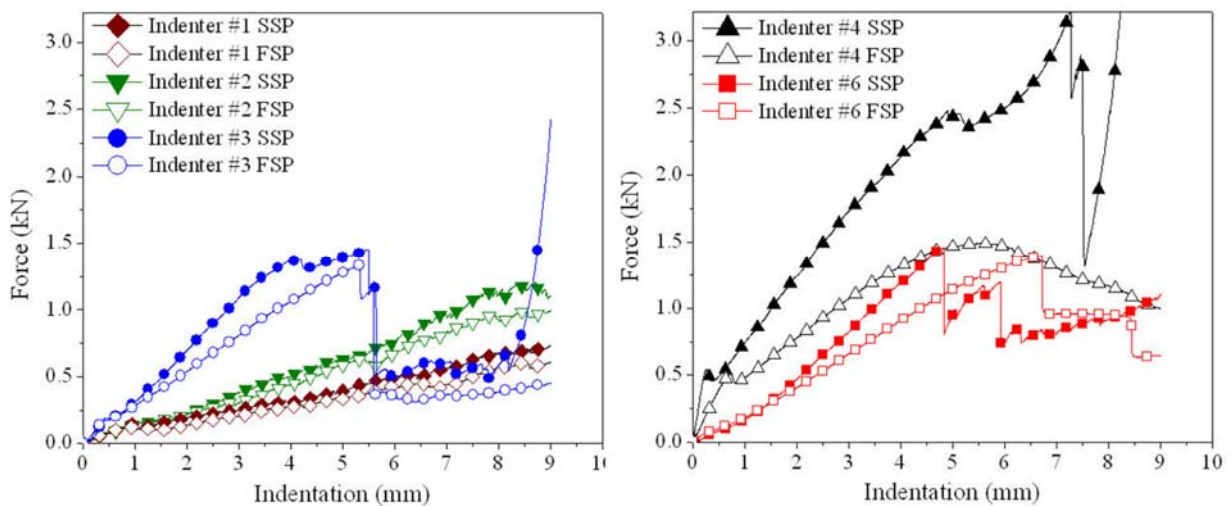


Figure 5 Force-indentation curves for solid and framed supporting plates and different indenters with Rohacell 51WF foam cored sandwich panels

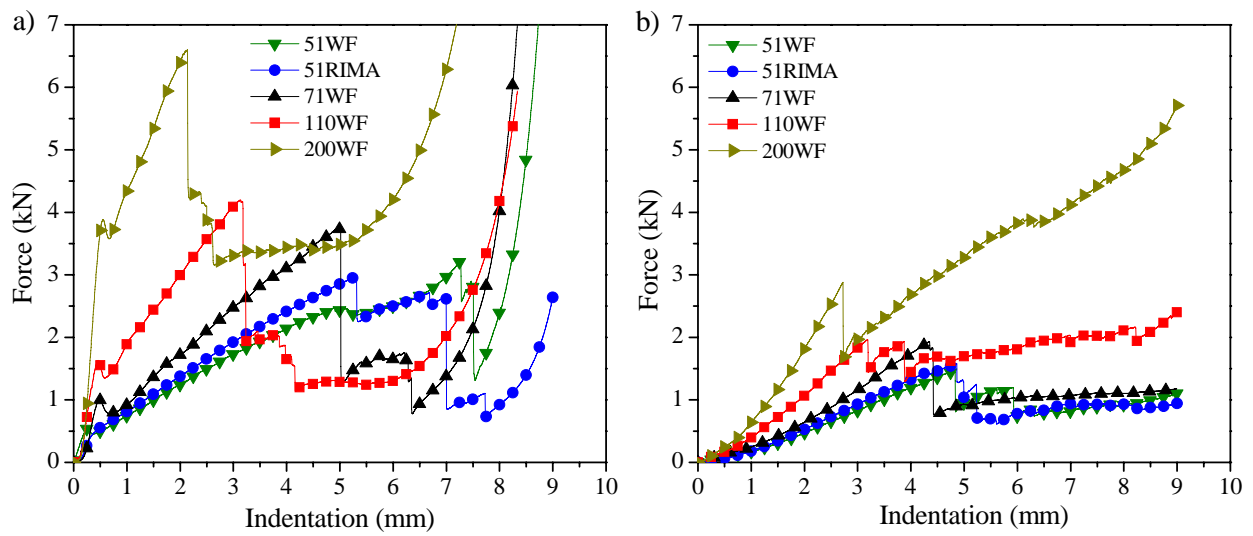


Figure 6 Force-indentation curves using a) indenter #4 and b) indenter #6 for sandwich panels with a variety of Rohacell foam cores

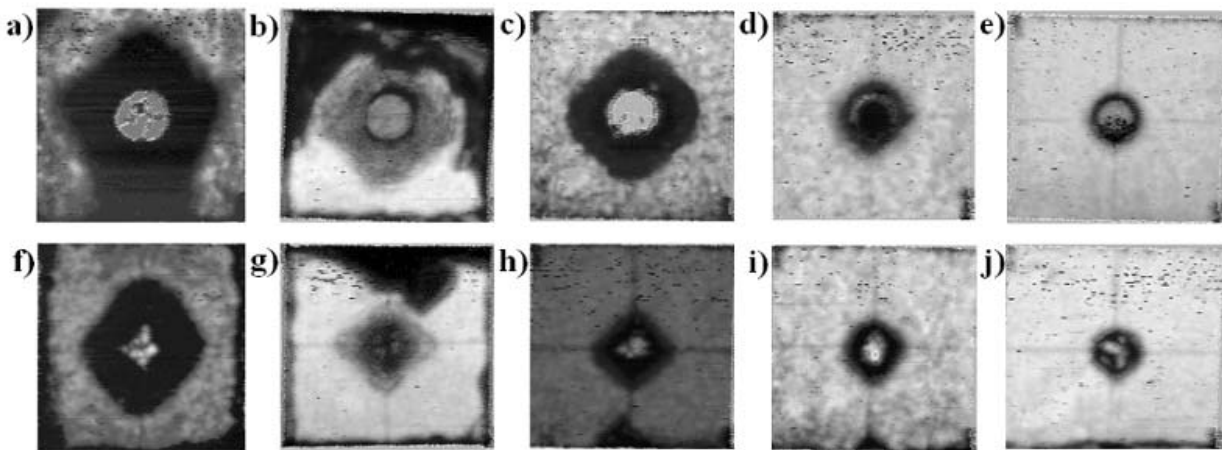


Figure 7 C-scan images of indented sandwich panels using indenter #4: a) 51WF, b) 51 RIMA, c) 71WF, d) 110WF, e) 200WF; using indenter #6: f) 51WF, g) 51 RIMA, h) 71WF, i) 110WF, j) 200WF

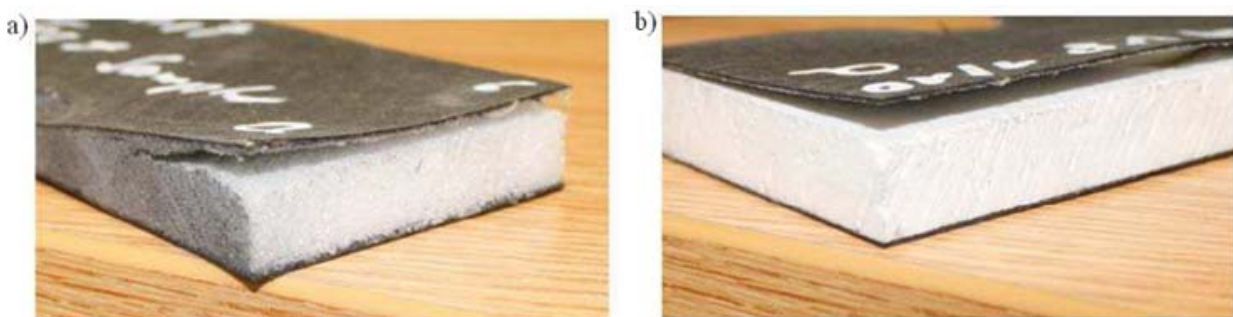


Figure 8 Failure by skin/core debonding: a) Rohacell 51WF, b) Rohacell 51RIMA

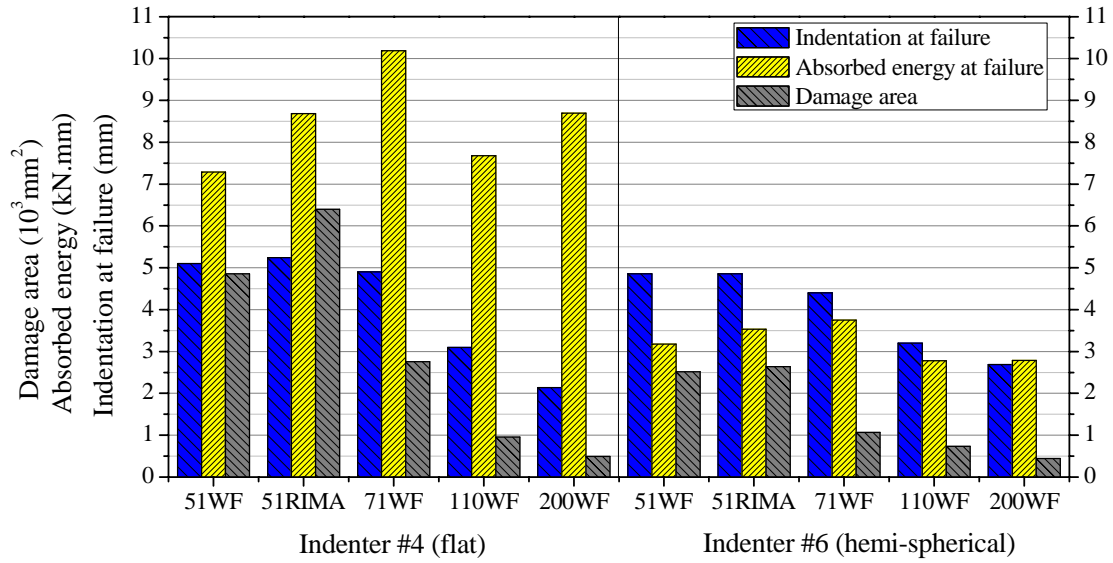


Figure 9 Absorbed energy and indentation at failure and damage area for sandwich panels with a variety of Rohacell foam cores and indenters #4 and 6

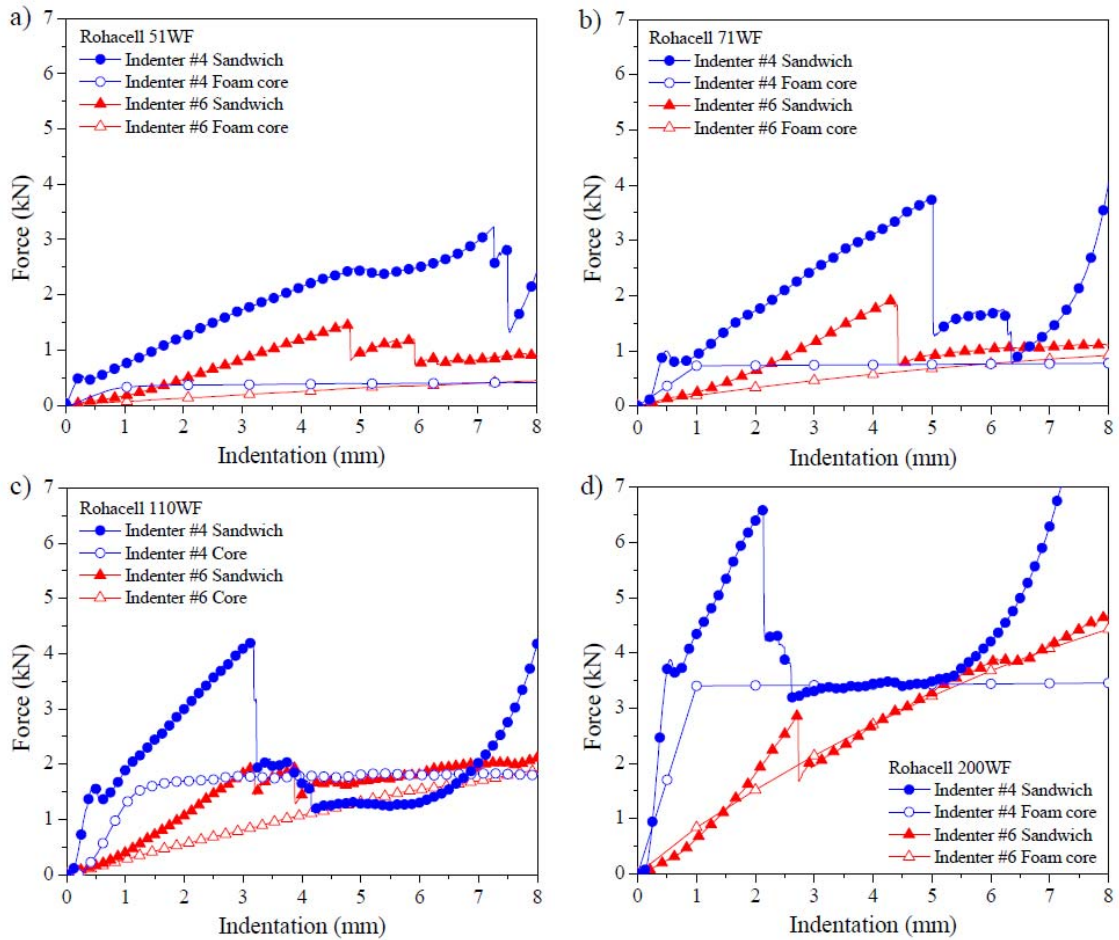


Figure 10 Force-indentation curves using indenters #4 and 6 for sandwich panels and their corresponding core materials: a) Rohacell 51WF, b) Rohacell 71WF, c) Rohacell 110WF and d) Rohacell 200WF