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Effect of face sheet material on the indentation response of metallic foams

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Abstract Sandwich panels comprising metallic foam cores fail by localized indentation when subjected to impact and blast loads. In this paper the indentation response of aluminum foams with face sheets, whose behavior represent elastic, elastic–ideally plastic and elastic–plastic strain hardening, were investigated experimentally under quasi-static loading conditions. The tests were carried out using flat and hemispherical indenters made of stiff tool steel on the blocks of aluminum foam with and without face sheets. Thickness of the face sheets was varied from 0.5 mm to 1.0 mm to evaluate the thickness effect on the indentation behavior. Competing failure modes for the initiation of failure are discussed. Results show that the indentation behavior is strongly dependent on the type and thickness of the face sheets used.

Introduction

Variety of engineering alloys such as Al, Fe, and Ni etc. can be foamed to a wide range of relative densities using various manufacturing techniques [1]. Depending on the process technique employed, either open cell structure or closed cell structure can be obtained in the metal foams. Aluminum based foams are the most famous among all metal foams as they offer good combination of properties such as high specific stiffness and strength, good corrosion resistance, recyclable and can be produced to near isotropic and homogeneous cellular structures [2].

Performance of Al foams can be enhanced by using it as core material in a sandwich, with strong and stiff face sheets. This is due to the lightweight and high strength of the resultant sandwich structure. However, these structures are sensitive to damage when subjected to localized loading like indentation because of the low strength of the core and low bending stiffness of the thin face sheets [3]. Rizov et al. [4, 5] have studied the local indentation response of polymeric foams with and without fiber reinforced polymeric composite face sheets both experimentally and numerically. The measured load–displacement response and residual indentation depth compared well with the finite element predictions. Most of the previous studies on sandwich structures comprising metal foam cores by various researchers focused on damage mechanisms and models for collapse mechanisms under various loading conditions [6–9]. Initial crushing followed by cell wall tearing was found to be dominant mechanisms for these foams under indentation loading with flat, spherical and conical punches.

Miller [10] used finite element analysis to study the behavior of a sandwich structure with metal foam as core and aluminum as face sheets and proposed a model for initiation load for indentation. Sridhar and Fleck (Unpublished) have found various failure modes for simply supported sandwich circular plates consisting

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of metal foam as the core and aluminum face sheets loaded centrally by a flat punch. They found core indentation, core crushing, face sheet punching, and face sheet bending as competing failure modes and the operating failure mechanism depends up on the plate geometry, punch radius and material properties.

Properties of the sandwiches varies if the metal foam core is sandwiched between different face sheets like aluminum, stainless steel, carbon fiber reinforced polymer (CFRP) matrix composite and alumina face sheets. Sandwich panels may be subject to indentation failure due to localized loading, for example accidental drop of heavy tools.

In the present work, indentation studies were carried out on an aluminum alloy foam (namely Alporas) blocks bonded to different type of face sheets under indentation loading with flat and spherical punches. Face sheet materials representing elastic–brittle and elastic–plastic behavior are chosen. The scope of the experimental investigation is further limited to a finite size of the specimens. In the following, first we describe the materials; experimental procedures adopted and then discuss indentation response along with observed failure modes in the results and discussion section.

Suppose a block of rectangular cross-section of width, *b*, and same length, with upper face sheet of thickness, *t* and foam core of thickness, *c* is subjected to indentation loading with the indenter of diameter 2*r* and the block is assumed to be supported by strong and stiff base as shown in Figure 1(a). When this metal foam block with face sheet is loaded by a flat punch at the center then it can fail in various failure modes namely core indentation, core crushing, face sheet punching, and face sheet bending. Under core indentation, the foam core directly beneath the indenter crushes and a plastic zone is developed beneath the indenter and this zone also extends beyond the edges of the indenter, by some radius λ, bending the face sheet to accommodate the foam deformation. A schematic diagram for this type of failure is shown in Fig. 1(b). In core crushing failure, the foam core crushes uniaxially due to the movement of the face sheet beneath the indenter. A schematic diagram for this type of failure is shown in Fig. 1(c). Under Face sheet punching failure mode, the rigid indenter punches through the face sheet around the sharp circumferential edge of the indenter while crushing the foam core beneath it. A schematic diagram for this type of failure is shown in Fig. 1(d). In face sheet bending failure, the face sheet starts to bend when displacement of the indenter increases. A schematic diagram for this type of failure is shown in Fig. 1(e). When a metallic foam block with face sheet is loaded by a spherical punch under quasi-static conditions, local indentation is going to be the dominant failure mode for indentation depths equal to that of punch radius.

Experimentation

The materials involved in this study and their mechanical properties characterization is briefly explained in this section. Experimental protocol adopted for the indentation of foam blocks with and without face sheets is described.

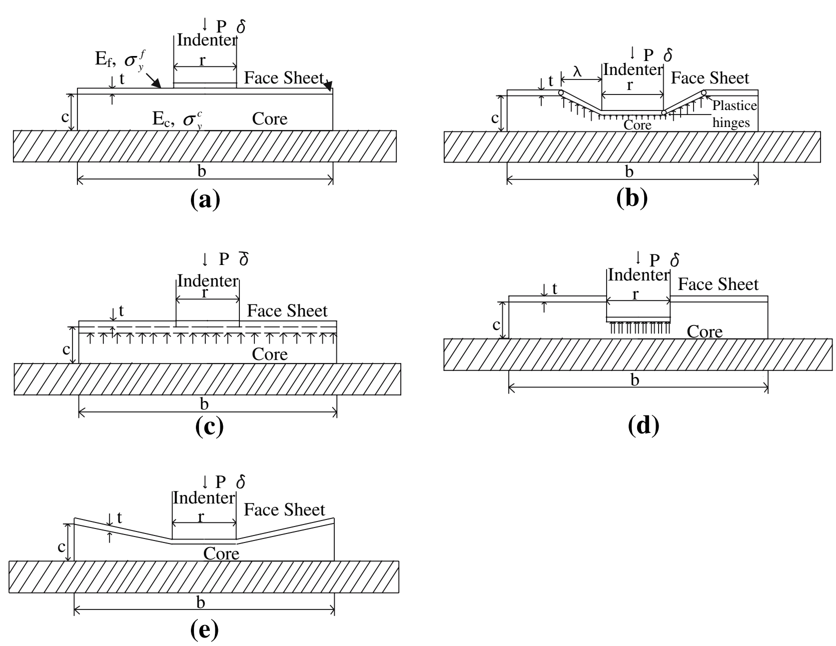

Fig. 1 Failure modes for sandwich beam under indentation loading (**a**) sandwich of metal foam core under indentation, (**b**) indentation failure mode, (**c**) core crushing failure mode, (**d**) face sheet punching, and (**e**) face sheet bending

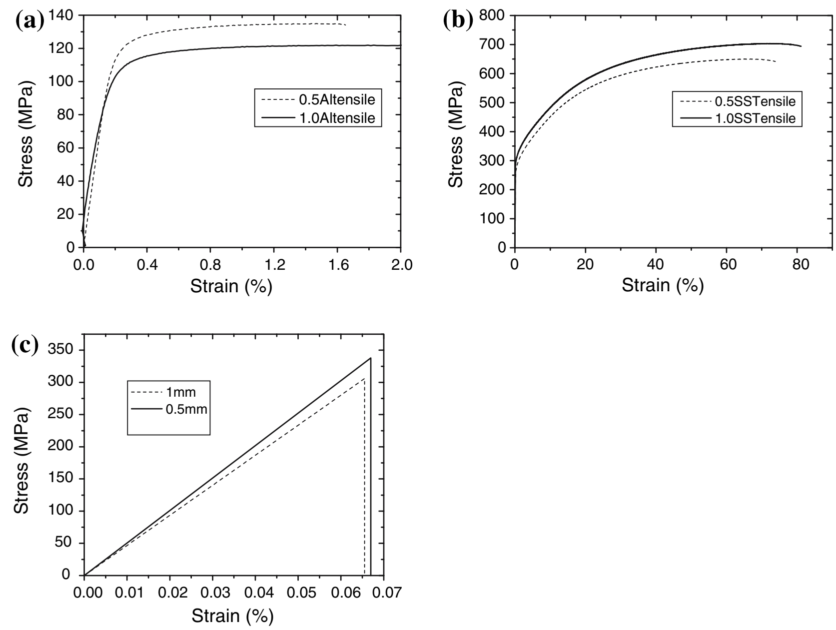

Fig. 2 Uniaxial stress–strain response of (**a**) half-hard aluminum representing elastic-perfectly plastic behavior and (**b**) stainless steel sheet representing elastic-strain-hardening plastic behavior (**c**) alumina sheets under four-point bending

Materials and measured properties

Foam core

Alporas® closed cell Al foam with an average relative density of 9.5% was used as core material for sandwich structures as it is reported to be the most homogenous cellular structure [2]. Uniaxial tensile, compression and double-lap shear tests are conducted on the foam specimens using an Instron Universal Testing Machine *5567* under displacement control at a crosshead speed of 0.1 mm/min and the measured tensile strength, compressive strength and shear strength (for 20 mm foam) were 1.51, 1.85 and 1.01 MPa respectively [11].

Face sheets

Various types of face sheets including aluminum, stainless steel, alumina and CFRP matrix composite sheets were used as upper face sheet for the construction of blocks of metal foam sandwiches. A total of three type of face sheets were considered in this study: elastic–brittle (alumina and CFRP), elastic-perfectly plastic (aluminum alloy 1100) and elastic–plastic strain hardening (stainless steel 314) in nature. Two thicknesses (i.e. 0.5 and 1.0 mm) of face sheets were considered.

Tensile properties of aluminum (Al) and stainless steel (SS) sheets with different thicknesses were measured by conducting uniaxial tensile tests according to ASTM standard E8-04. Aluminum was found to have nearly elastic-perfectly plastic response as shown in Fig. 2(a), while stainless steel shows some strain hardening behavior (see Fig. 2(b)). CFRP matrix composite laminates were made from unidirectional carbon fibers prepregs[1] (of 0.16 mm) impregnated with epoxy matrix by hand lay up technique: required number of prepreg sheets were stacked together and cured at 120 °C at a nominal pressure of 0.1 MPa in a vacuum bag mold for 2 h. Alumina (Al_2O_3) face sheets are tested under four point bending. Alumina and CFRP face sheets were found to be linear elastic till fracture. Linear elastic behavior for alumina sheets is shown in Fig. 2(c) [12, 13]. The measured properties for all the face sheets are summarized in Table 1.

Test specimen preparation and experimentation

In the present investigation, Alporas® foam of 70 mm length, 70 mm wide and 25 mm thick were bonded to four types of face sheets as described above using Redux 322 epoxy adhesive [13]. Foams with various face sheets are indented at the center using a flat punch of 25 mm diameter and also with a spherical punch of 25 mm diameter. Ratio of different sizes depending upon the cell size, indenter diameter, specimen dimension and indentation depth, affect the load displacement response in indentation loading [14]. So precautions were taken care in choosing those parameters in this study to over come these size effects. It is to be noted that the ratio of indenter diameter (25 mm) to cell size (3.0 mm) exceeds 8 and according to Olurin et al. [6] and Andrews et al. [7] no significant

[1] Supplied by Hexel Composites, Australia.

Table 1 Mechanical properties of face sheets

Sheet	Thickness (mm)	Strength (MPa)
Al	0.5	135 (tensile)
Al	1.0	120 (tensile)
SS	0.5	650 (tensile)
SS	1.0	700 (tensile)
Alumina	0.5	338 (bending)
Alumina	1.0	302 (bending)
CFRP laminate [12]	2.0	1,900 (longitudinal tensile)
CFRP laminate [12]	2.0	1,050 (longitudinal compressive)

effect of cell size on indentation pressure will be noticed. Edge effect become negligible if the gap between the two indentation in the same specimen is more than one indenter diameter and the distance from indentation to free edge is also more than or equal to one indenter [7, 15]. In the current study, the distance from free edge to indenter was kept around one indenter diameter (22.5 mm) so the edge effect would be negligible on the load–displacement behavior. If the distance between indentation to free edge would be lesser than one indenter diameter then less resistance would have been applied by foam cells and there would be a down fall in slope of load–displacement curve. Similarly if the indentation depth would have been increased more than 13 mm then load and displacement response would be very steep in later stages of experiments for almost all the blocks. According to Kumar et al. [9] if the indentation depth exceeded more than half of the thickness of specimen then the indentation response is affected by the back support and lead to very steep behavior afterwards. In our experiments indentation depth was kept constant at 8 mm which is much lesser than the half of the specimen thickness (12.5 mm). All the tests were conducted under displacement control with a cross-head movement of 0.5 mm/min. Indented specimens were sectioned by electron discharge machining (EDM) for observing the damage zone using Surface Displacement Analyser (SDA). But because of non-conduciveness of adhesive, EDM failed to machine the specimen at sites where foam was crushed and adhesive was present so those sites were cut later by bench saw at low speeds.

Results and discussion

Face sheet bending, core indentation, adhesive bond failure between the core and face sheet were recognized as active failure mechanisms for aluminum foam blocks with different face sheets under spherical and flat indenters. Here, behavior of those blocks is discussed in detail along with the analysis of damage zone.

Indentation using flat indenter

The load–displacement response of Alporas® foam with and without various face sheets under a flat indenter is shown in Fig. 3(a, b) for 0.5 mm thick and 1.0 mm thick face sheets respectively. Here, initial peak load was observed followed by a long plateau indentation load. This curve is similar to the foam's response under uniaxial compressive loading [11]. First peak during loading represents the start of collapsing of the foam cells beneath the indenter and tearing of the cells at the periphery of the indenter. Similar observations were reported by Olurin et al. [6] and Kumar et al. [9]. The indentation failure load can be represented in terms of punch radius r and uniaxial compressive strength of the foam σ_c^y as $\pi\left(r^2\sigma_y^c + 2r\gamma\right)$, where γ is the tearing energy of the foam [6]. The computed indentation load of 1.65 N with tear energy of 9.0 N/mm for 9.5% relative density Alporas® foam agrees well with the present experimental measurements.

Load initially increases linearly with the extent of indentation in the case of Alporas® foam block with elastic-perfectly plastic aluminum face sheets and slope is representative of the structure's stiffness. After initial failure at which the face sheet starts yielding the load remains constant with indentation. With further loading, the face sheet bends as depicted in Fig. 1e and there is a strong hardening response due to stretching and bending of the face sheet. After reaching to a peak load the indenter punches through the face sheet and the core beneath it leading to the sudden drop in the load due to reduction in the stiffness. Similar kind of observations was found in blocks with both 0.5 and 1.0 mm face sheet thicknesses. The failure mode is face sheet bending rather than local core indentation.

In the case of stainless steel face sheets, the initial failure is triggered by the face sheet bending and there is a strong hardening behavior due to membrane stretching and bending effect. With further indentation, the bond between the face sheet and core failed by detachment of SS face sheet from the adhesive. This failure initiated at the outer corners of the block and with this failure the hardening rate reduced. Face sheet punch through was not observed for the tested geometries.

The indentation response of the sample blocks with alumina face sheet shows linear elastic behavior up to

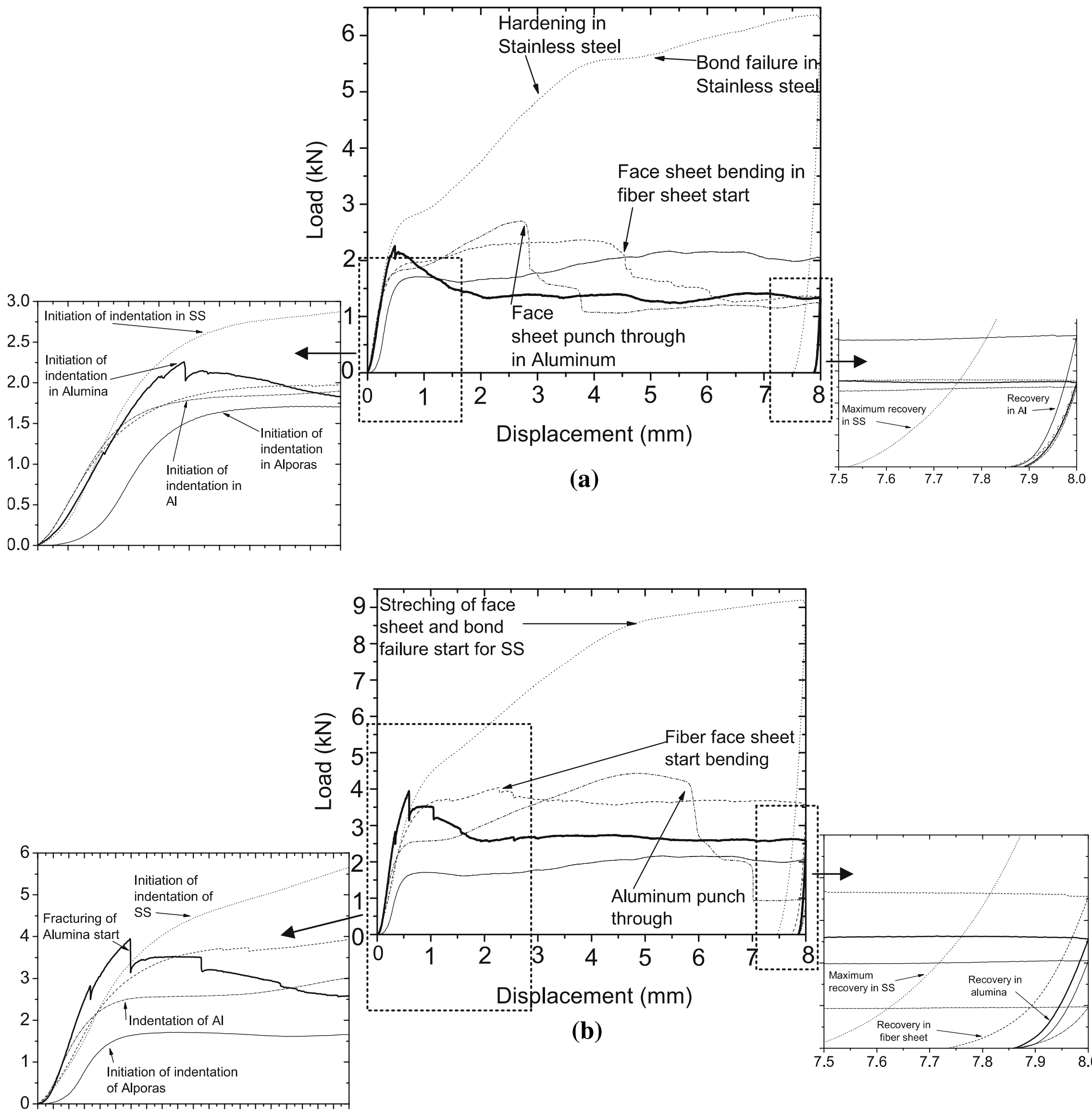

Fig. 3 Comparison of experimental indentation behavior of foam with different face sheets under flat indenter (**a**) 0.5 mm face sheet thickness (**b**) 1.0 mm face sheet thickness

the peak load and then cracking of alumina occurs around the circumference of the punch due to high stress concentration. This shows that the load for indentation includes the resistance from the foam to collapse beneath the indenter and the load required to fracture alumina on punch circumference. The sample block with 0.5 mm thick alumina was punched through at the onset of failure and continued with the crushing of the foam beneath the indenter. In the case of sample blocks with 1.0 mm thick alumina the face sheet, cracking occurred gradually and the punch-through happened in the later stages of indentation.

Face sheet bending was observed to be the failure initiation mechanism for sample blocks with CFRP composite face sheet. At the beginning of the test, the load increased linearly with loading, after initiation of failure due to face sheet bending the non-linearity in load–displacement appears. Face sheet bending was found to be a failure mechanism in those blocks because of the appearance of bending curvature which was established only in the fiber direction within the zone of punch diameter. Furthermore, face sheet punching appears to be one more failure mechanism happening in those blocks which is represented by sudden drop in load. Clear punch-through was noticed in the face sheets with 0.5 mm thick carbon fiber reinforced plastic laminates, whereas in 1.0 mm thick face sheets only bending of the face sheets occurred.

These results corroborate the findings of Shuaeib and Soden 15] who observed similar behavior of sandwich beams with PVC foam core and glass reinforced plastic face sheets. Upon unloading maximum elastic recovery was noticed in foam blocks with SS face sheets and minimum with alumina face sheets.

Top view of the indented blocks with different face sheets of thickness of 0.5 mm, under flat indenter are shown in Fig. 4. For the considered test geometries the failure mechanism varied from foam indentation, to face sheet bending or face sheet crushing depending upon the face sheet type.

Indentation with spherical indenter

The responses of Alporas® foam with and without various face sheets under spherical indenter are shown in Fig. 5(a, b). The load increases continuously with indentation without any initial failure for foam block without any face sheet under indentation. The reason for this hardening in load–displacement curve is due to the incremental increase in contact area between the indenter and test block, representative of geometric hardening. In fact, the indentation depth has not reached to the full radius of the indenter and therefore the behavior is different in latter stages as observed by Kumar et al. [9].

Initially load increases linearly with indentation depth in response to the stiffness of the structure for foam joined to metallic face sheets. But the initial elastic response is very shallow. The failure mode in this case is essentially due to local indentation beneath the spherical punch. The face sheet material has to stretch to accommodate to the punch profile. The hardening is due to both bending and stretching of the face sheet. The rate of hardening increases with increasing thickness of the face sheet and strain-hardening exponent. Except in the case of Al face sheets with 0.5 mm thickness, no visible tearing of the metallic face sheets was observed beneath the punch.

The indentation response of the foam block with alumina face sheets shows localized cracking of alumina at the periphery of contact, due to the generation of high tensile stresses which is a clear local indentation failure. The crushing of alumina was due to very high shear stresses at the edge of the indenter. At larger indentation depths, not much difference was found between responses of the foam indentation with that of foam with $Al_2 0_3$ face sheet.

A few transverse cracks were found in the face sheet during indentation of the sample block with carbon fiber reinforced plastic face sheet. The occurrence of these cracks is due to the low transverse strength of these laminates as compared to the longitudinal strength. Face sheet bending was observed to be dominant failure

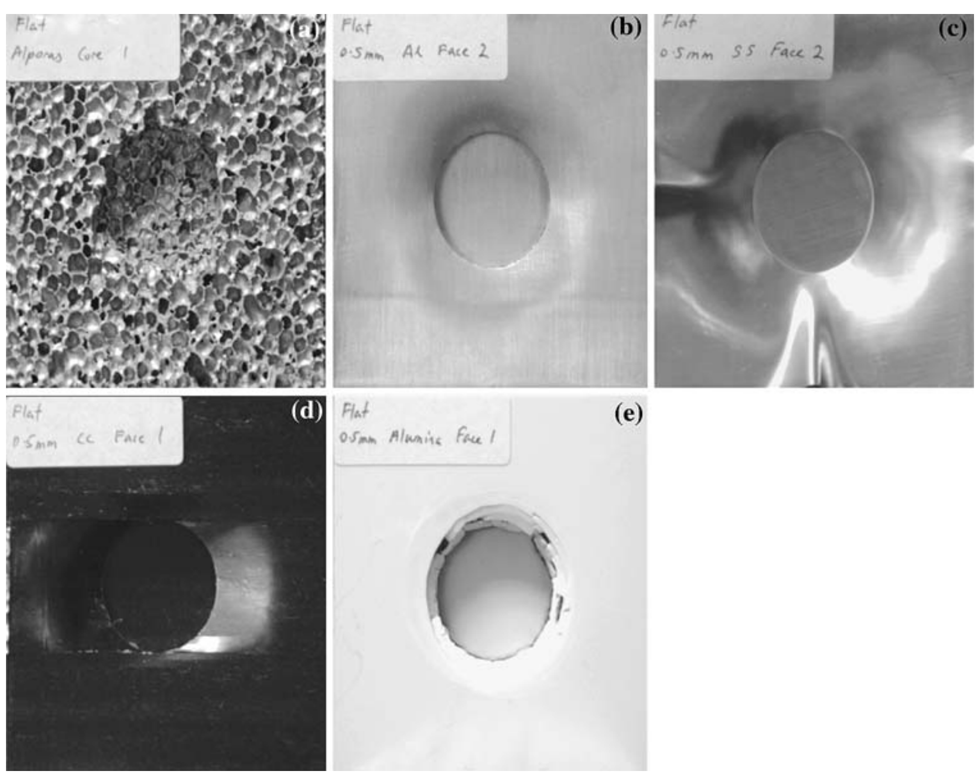

Fig. 4 Top view of the indented specimens having 0.5 mm thick face sheet under flat indenter (**a**) Alporas alone, (**b**) Al face sheet, (**c**) SS face sheet, (**d**) CFRP face sheet, and (**e**) Alumina face sheet

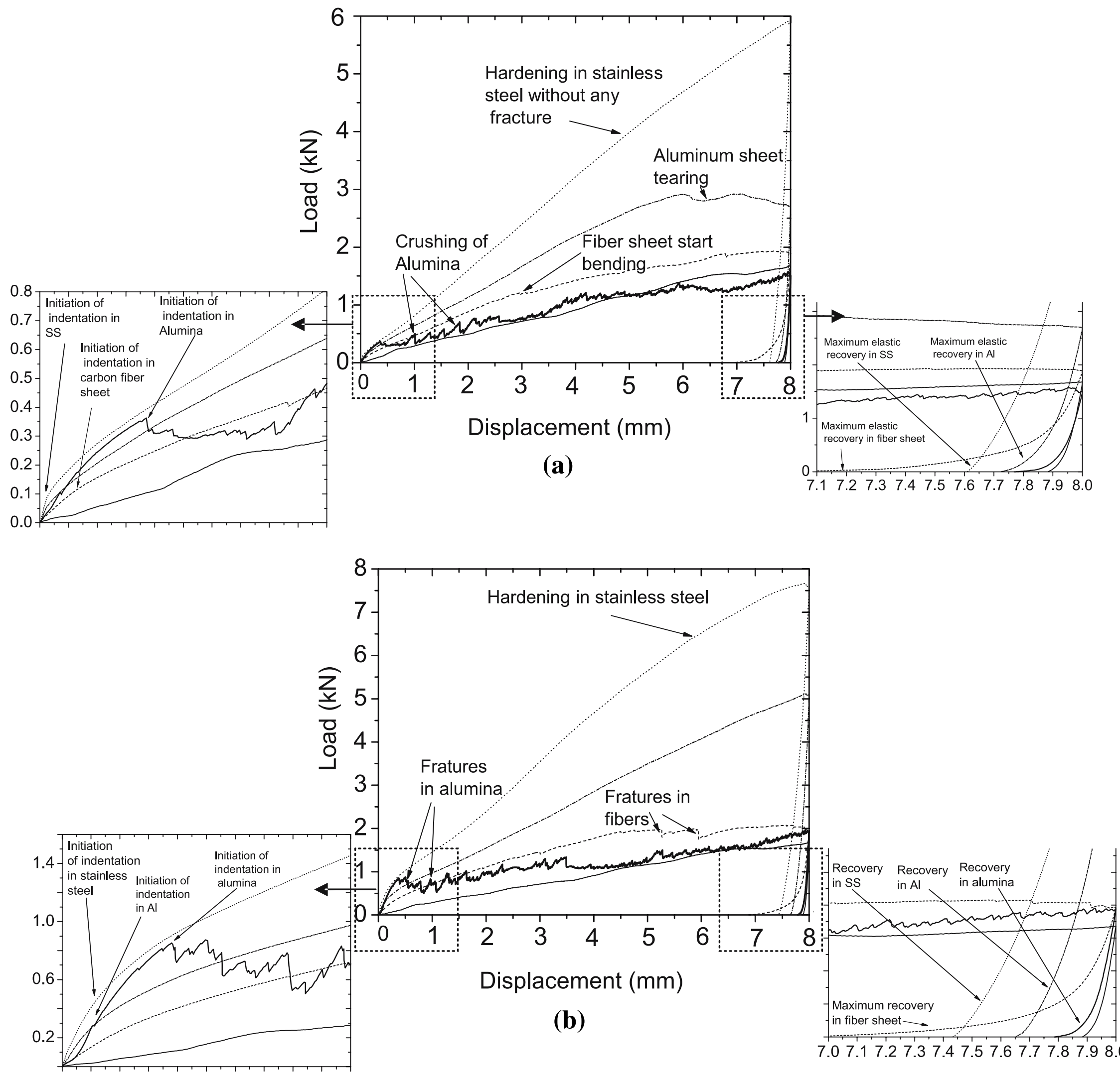

Fig. 5 Comparison of experimental indentation behavior of foam with different face sheets with spherical indenter (**a**) 0.5 mm face sheet thickness, and (**b**) 1.0 mm face sheet thickness

mechanism for this type of sample block. Also, maximum elastic displacement recovery after indentation among all other sample blocks having different face sheets is observed due to high elastic stiffness of CFRP: displacement recovery of around 1 mm was found in the sample block having 1.0 mm thick face sheet while for 0.5 mm face sheet block this recovery was found to be lesser.

Top view of foam blocks with different 0.5 mm thick face sheets indented using a spherical indenter are shown Fig. 6. Local core indentation along with face sheet failure seems to be the dominant failure mechanism.

Morphological aspects of damaged zones

Cross-sectional views of the foam blocks after indentation with flat and spherical punches are shown in Fig. 7 with a uniform magnification factor and are discussed briefly in the following section.

Cross-sectional macroscopic view of the indented Alporas blocks with flat and spherical indenters is shown in Fig. 7(a, b) respectively. Foam cells got crushed locally underneath the indenter and it was severe in the case of flat punch than that of spherical punch for the same indentation amount. This is due to the fact that the area of contact increases gradually with indentation depth in the case of spherical punch and remains constant at 491 mm^2 for flat punch.

Figure 7(c) reveals the indentation behavior of foam cells with flat indenter having Al face sheet of 0.5 mm thickness. Area in which the cells were collapsed was marked in the figure. Damage zone was predominant underneath the flat punch and face sheet punch

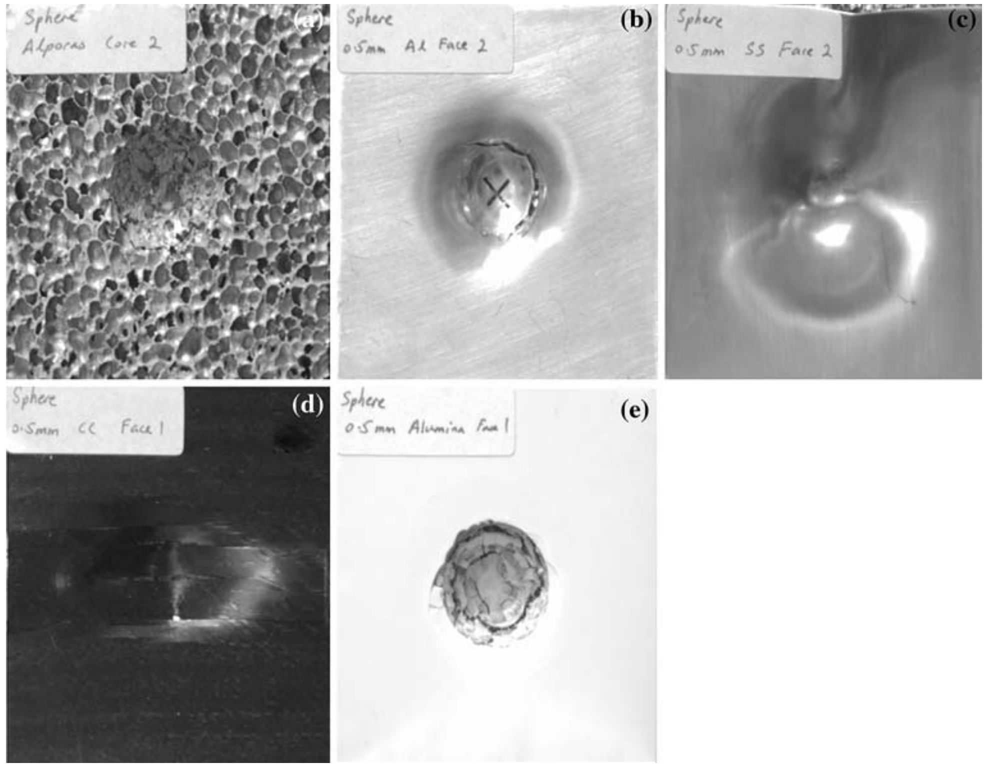

Fig. 6 Top view of the indented specimens having 0.5 mm thick face sheet under spherical indenter (**a**) Alporas alone, (**b**) Al face sheet, (**c**) SS face sheet, (**d**) CFRP face sheet, and (**e**) Alumina face sheet

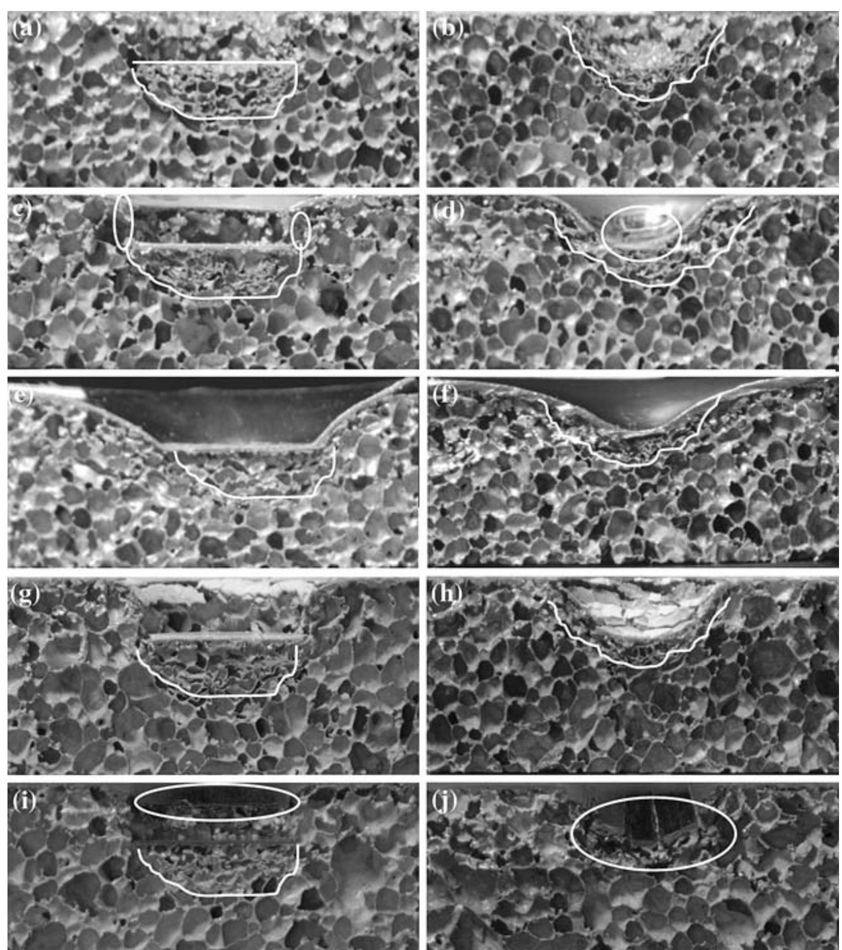

Fig. 7 Cross-sectional view of the indented foam blocks with different face sheets under indentation (**a**) Alporas with flat indenter (**b**) Alporas with spherical indenter (**c**) foam block with Al sheet of 0.5 mm thickness under flat indenter (**d**) block with Al sheet of 0.5 mm thickness with spherical indenter (**e**) foam block with SS sheet of 0.5 mm with flat indenter (**f**) foam block with SS sheet of 0.5 mm thickness with spherical indenter (**g**) foam block with alumina sheet of 0.5 mm thickness with flat indenter (**h**) foam block with alumina sheet of 0.5 mm thickness with spherical indenter (**i**) foam block with CFRP sheet of 0.5 mm thickness with flat indenter (**j**) foam block with CFRP sheet of 0.5 mm thickness with spherical indenter

through was observed (see the elliptical mark). Local cell wall collapse along with foam cells cracking was observed when foam blocks with 0.5 mm thick Al face sheets were indented by a spherical punch (see Fig. 7(d)). Tearing of face sheet was also observed at which sudden drop in load has occurred in the load displacement curve of Fig. 5(a).

Cross-sectional macroscopic views of the indented blocks with 0.5 mm thick SS face sheets using flat and spherical indenters are shown in Fig. 7(e, f), respectively. Area in which the cells were collapsed is highlighted in the figure. Punching of face sheet was absent in SS sheet with flat indenter because of its high strength. Face sheet bending is the failure mechanisms for all the blocks with SS sheets when indented by flat punch. Local indentation beneath the indenter is the failure mode when indented by spherical punch.

Cross-sectional macroscopic views of the indented blocks with 0.5 mm thick alumina face sheets using flat and spherical indenters are shown in Fig. 7(g, h), respectively. Punching of face sheet is shown in the figure with flat indenter because of its low tensile strength at the indenter periphery. Local indentation beneath the indenter is found to be the failure mode when indented by spherical punch. Figure 7(i, j) shows the macroscopic views of the indented blocks with 0.5 CFRP sheets using flat and spherical indenters respectively. Here bending curvature marked by ellipse in the Fig. 7(i) in face sheet indicate the initial failure mechanism using flat punch to be face sheet bending. Punching of sheet was also seen to be later failure of block. Transverse cracking is observed in CFRP sheet with spherical punches with bending of sheets, which indicate that initial failure mechanism for block with CFRP sheet is face sheet bending with final mechanism of face sheet punching.

An overview of mechanisms for failure initiation and its value with different face sheet materials in shown in Fig. 8 for both flat punch and spherical punch indentation. For the geometry and materials system considered here, the failure initiation mechanism and mode for flat punch depends upon face sheet constitutive behavior and strength, while the trend was affected negligibly with the effect of thickness of face sheet. With increasing face sheet thickness, the normalized failure load increases too. In the case of spherical punch indentation, the brittle face sheet doesn't enhance indentation initiation failure load: only ductile aluminum and SS are useful for energy absorption.

Energy absorption

A comparison of energy absorbed by blocks with different face sheets with flat and spherical indenters are shown in Fig. 9(a, b), respectively. Energy absorption was estimated by measuring the area under the load–displacement curve individually. Energy absorbed by blocks with flat indenter is found to be more than those indented by spherical indenters. With increasing thickness of the face sheet, absorbed energy is also increased because of the increased volume. Trend in absorption of energy by blocks with different face sheet materials was found to be similar for both the types of indenters. Under flat indenter, absorption of energy for the blocks without any face sheet and with elastic face sheet of thickness of 0.5 mm is almost the same. It may be due to cracking of those face sheets appear in early stage of indentation.

Energy absorbed by foam block with face sheet with spherical indenter was found to be more than without face sheet. Maximum energy was absorbed by foam block with elastic plastic sheet furthermore, foam block with elastic perfectly plastic sheet absorbed more energy than elastic face sheet. Similar trend is missing in flat indenter because of lower absorption of energy by Al sheets due to punch through.

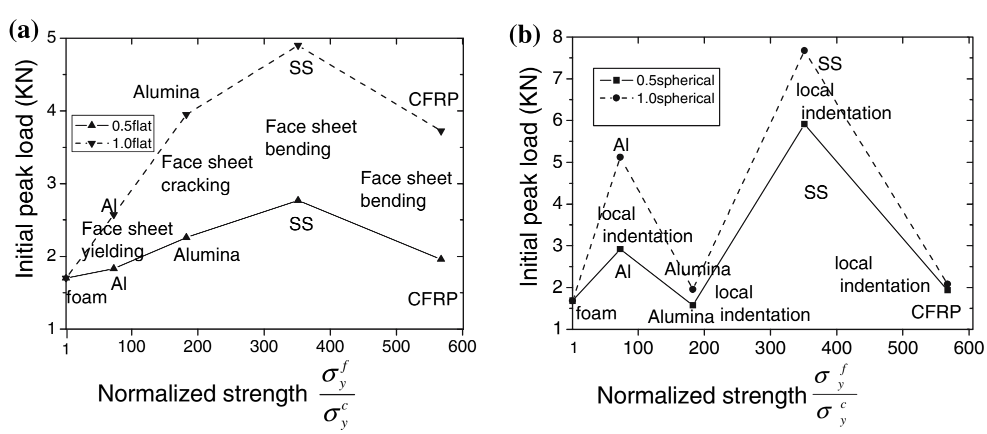

Fig. 8 Comparison of initial peak for indentation versus strength ratio of face sheet to core (**a**) under flat indenter, and (**b**) under spherical indenter

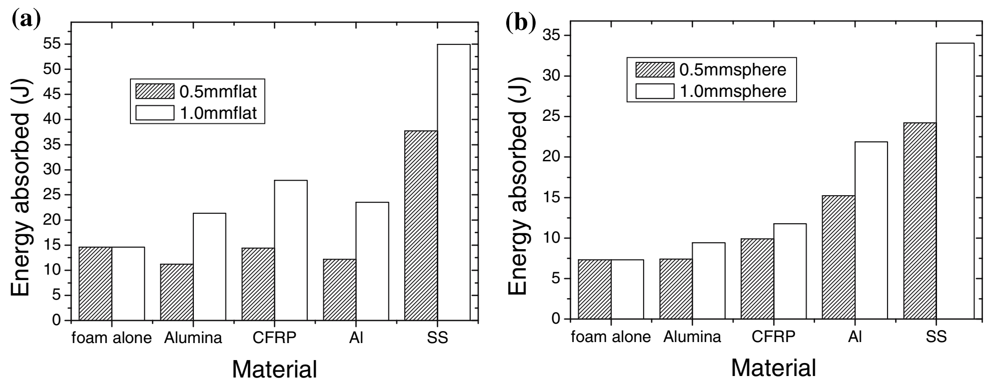

Fig. 9 Energy absorption by blocks with different face sheets (**a**) under flat indenter (**b**) under spherical indenter

Conclusions

Sample blocks with aluminum foam core and various face sheets were studied under indentation loading. Foam core collapsing and tearing at the periphery of indenter were found to be the failure mechanism for samples without any face sheet. Various failure mechanisms were observed for the foam blocks having different face sheets under indentation loading, depends on factors such as face sheet constitutive property, thickness and indenter geometry.

These are different failure mechanisms involved, such as face sheet bending in block with CFRP sheet, face sheet punching in block with Al sheet, core indentation in block with alumina sheet, bond failure in block with SS sheet etc. Constructing a failure map and showing the dependency of failure mode on various parameters such as face sheet thickness, nature, core etc, is beyond the scope of this paper because of the complexity of failure mechanisms for these blocks due to the additional factor of face sheet material.

As precautions were taken for selecting the sizes of specimens and indenters, so load–displacement response with failure mechanism is not affected by size effects. But if different size ratios chosen which do not satisfied the size rule then the load–displacement response would be different with different failure mechanism compare to that in the present study. From this study, it is clear that the type of indenter also plays an important role in response of these blocks under indentation. So the response of conical indenter would be different in terms of failure mechanisms and load displacement behavior which will be analyzed in future for better understanding of effect of indenters on foams with different sheets.

It is worth mentioning here that the indentation response of foams especially Alporas depend upon the loading rate, which can differ by 34% in plastic collapse strength and energy absorption [9]. So the failure mechanism appeared here could be different for another loading rate because foam collapsing is one factor contributing in the failure of blocks.

This work will be continued by studying the changes of parameters such as size of the blocks, indentation depth and type of foam, in order to have more through understanding of foam indentation failures.

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