FEM modelling of single-core sandwich and 2-core multilayer beams containing foam aluminum core and metallic face sheets under monolithic bending

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Abstract: This present paper dealt with bending deformation and failure behavior of sandwich and multilayer beams composed of aluminum foam core and metallic face sheets by finite element method (FEM) and four-point bending test. Results revealed that collapse of the multilayer beams is dominated by two basic modes: indentation (ID) and core shear (CS). ID is dominated by the maximum compressive strain and CS by the maximum shear strain. The failure of the sandwich beams depends on if the face sheets show ID mode in the multilayer beams or otherwise. If a multilayer beam is dominated by ID mode, the sandwich beams with similar face sheets and same core thickness would also show ID characteristic. If a multilayer beam fails fully by CS mode, no ID characteristic would appear in similar face sheet single-core sandwiches. Beams failed by ID mode have a potential to consume more bending deformation energy than those dominated by CS mode. The dense foam can bear higher loading, which in turn, increases the ability of absorbing deformation energy for a beam. In applications of deformation energy absorption aspect, beams containing foam core and metallic face sheets should be designed to have a tendency of ID mode failure.

Key words: aluminum foam; finite element method; sandwich and multilayer beams; indentation; core shear

1 Introduction

Metallic foam is a relatively new class of material that offers novel mechanical, electrical, acoustic and thermal properties. Thus, there is increasing potential in the use of this material in a variety of applications to compete favorably with polymer foams as the lightweight cores of sandwich beams, plates and shells, due to the low density, high stiffness and high temperature capability. Mechanical properties of the monolithic aluminum foam, such as the elastic modulus, plastic collapse stress, fracture toughness and fatigue behavior, have been described by theoretical and numerical analyses of honeycomb structure[1–4] and experiments of practice aluminum alloy foams[5–15]. It has been suggested that relative density \(\rho'\) (defined as ratio of bulk foam density \(\rho_b\) to cell wall density \(\rho_c\)) plays an exponen real role in mechanical response of the aluminum foams. In the mechanical response, the foam shows a special deformation, called densification, under compressive loading. After uniform compression, the densification generates gradually throughout the compressed sample by cell wall bending. Crush band usually takes place within one cell dimension, followed by collapse of the adjacent layer with one cell dimension until the opposing faces of individual cell wall of the sample are touched. With progress of the densification, i.e., compressive strain, the strength increases[1–2, 9–10, 16]. The behavior of the densification is the reason why the metallic foam has a potential of absorbing deformation energy under static and dynamic loads.

However, the most application of the metallic foam is as core in sandwich or multilayer beams with solid face sheets. Purpose of the sandwich or multilayer beam design is to avoid low stiffness of the monolithic foam. A dramatic deformation or fracture work was achieved when the monolithic foam and metallic or ceramic sheet were combined as beam structure[17–18]. To understand toughening mechanisms of the beam structure, deformation and failure process of the beam structure containing aluminum foam core and solid face sheets is...
of prior issue with concern increasing. Three failure modes of these beams have been concluded[19–21]. They are face yield (or face breaking), indentation and core shear. Mechanism maps showing failure domains of each mode have also been discussed and constructed by BART-SMITH et al[19] and CHEN et al[21]. These maps identify regions of dominant failure, with ratios of core thickness to support span and face sheet thickness to support span as the coordinates. The predictions are in agreement well with experimental results under bending fracture and fatigue conditions[22]. For any new selected face sheet, boundaries of the failure regions must be recalculated.

In-situ surface displacement analysis has been used to probe the mechanisms of indentation and core shear[16–17]. Indentation is due to the localized collapse of the foam core adjacent to the loading point, while core shear corresponds to the discontinuously horizontal and vertical displacement of the core between the loading points of bending which leads to shear crack initiation, growth and collapse of the beam.

Due to the fact that a negligible literature about the mechanical responses of beams containing the foam core and solid face sheets has been published, deformation and strain analysis of the beam during monolithic bending should be preformed to understand and estimate the possibility of the failure modes in beams with different face sheets and geometries for the applications in energy absorption field. In this work, finite element method was used to analyze the deformation and strain throughout a beam under monolithic bending; the comparison of FEM results with experiments was also made. To understand the effect of the face sheet and the beam geometry on the deformation and damage of the beam, half-hard pure aluminum (HHPA) face sheets with different thickness, single-core (sandwich) and 2-core (multilayer) structures were chosen for simulation.

2 Experimental

2.1 Model geometry and boundary conditions

Finite element analysis using ANSYS 6.0® (Swanson Analysis, Inc.) was performed to estimate the deformation and strain distribution in the proposed beam structures under monolithic bending. PLANE 182 elements (four-noded quadrilateral structural elements) are selected for the analysis. The analysis is done using 2-D model for simplicity. By obtaining the distribution of strain within the structure, the most-likely-to-fail zones in the beam can be estimated and thus the failure modes can be obtained. The simulated results obtained can be compared with the experimental outcomes to assess the feasibility of using computer simulation to model the failure mechanisms.

The model geometry used in this analysis represents rectangular-shaped aluminium foam (Alporas) of varied thickness. As core, the varied thickness of the foam is associated with structure of the sandwich or multilayer beam. The optical image of Alporas is shown in Fig.1. The aluminum foam is represented with holes of irregular radii, spacing between any two holes and locations on the rectangular model. The holes represent the cells in the actual foam model and the average size of the holes is about 3.5 mm. Table 1 summarizes structures of the sandwich and multilayer systems designed in this work. Single-core sandwich and 2-core multilayer beams are simulated and tested in the study respectively.

![Optical image of Alporas](image)

**Table 1 Sandwich (single-core) and multilayer (2-core) beam design**

<table>
<thead>
<tr>
<th>Beam</th>
<th>Core thickness/mm</th>
<th>Half-hard pure aluminum face sheet thickness/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandwich</td>
<td>20</td>
<td>0.5, 1.0</td>
</tr>
<tr>
<td>Multilayer</td>
<td>10</td>
<td>0.5, 1.0</td>
</tr>
</tbody>
</table>

With reference to Table 1, $A_F$ and $A_L$ denote the symbols for the aluminum foam and the Al face sheet respectively. For terminology, symbol $A_L-A_{10-c20}$ stands for a single-core panel which contains Al face sheets and one foam core, the core thickness, $c$ and face sheet thickness, $t$ are 20 mm and 0.5 mm, respectively. Similarly, with reference to Table 1, for example, symbol $A_L-2A_{20-c10}$ represents a 2-core multilayer panel, and each core with thickness, $c$ and face sheet thickness, $t$ of 10 mm and 1 mm, respectively.

An axisymmetrical model is employed to reduce the processing time of data. Perfect bonding between layers is assumed. All of these assumptions prevail for all types of analyses. Figure 2 illustrates the degree of freedom constraints on the model. This is a typical FEM model of
sandwich with a single foam core of 20 mm and face sheets of 0.5 mm. Based on Fig.2, FEM models of other beams can be developed, simply through replacing the face sheets of 0.5 mm in Fig.2 by the face sheets of 1 mm for a sandwich, or just adding a middle face sheet for a 2-core beam. Since the model is symmetrical along the y-axis, constraints in the x-direction are placed along x=0 to signify the symmetry boundary condition. Constraint at position 1 represents the outer roller of the four-point bending. At position 1, constraint (i.e. displacement in the y-direction equals 0) is placed to prevent any movement of the model in the x-direction. Thus sliding along the x-direction is allowed. Loading and displacement are applied to position 2 (inner roller). Simulation results including normal strains, $\varepsilon_{xx}$, and shear strain, $\varepsilon_{xy}$, and von Mises equivalent strain, $\varepsilon_c$ were characterized.

![Fig.2 Applied boundary conditions on finite element model of a sandwich with a single core](image)

With so large size difference among the sandwich beam, cell and cell wall, the FEM model employed is very important for the simulation precision which depends tightly on the FEM mesh in model. For FEM mesh setting, we found some problems when we employed the finite element model as the actual foam. Due to the thickness of the cell (average 0.1–0.2 mm) wall is very smaller than the cell size (about 3.5 mm), sandwich size and face sheet thickness, so (1) if we set very fine mesh in the thickness direction of the cell wall, the detail information such as profile of the local buckling of the cell wall may be shown, however it was hard to see the panorama deformation of the cell and sandwich, besides, some unreasonable (non-convergent) strain contours were obtained on the cell wall, and (2) if we set coarse mesh in thickness direction of the cell wall, the detail strain contour on the cell wall is also lost. For these reasons, we have to enlarge the cell wall as the current rough model is employed. By this processing, the deformation panorama of beams, strain contour on the cell wall, as well as cell wall shear, can be clearly shown (see section 3.2). These strain contours on the cell walls are enough to describe the macro-deformation and failure behaviors of the beams, cells and even cell walls; even the profile of the excessive indentation which is accompanied by local cell wall buckling was missed.

2.2 Materials properties

The half-hard pure aluminum exhibits elastic-plastic behavior when it undergoes deformation. Thus linear elastic properties, namely, elastic modulus, Poisson’s ratio are inputted. Table 2 shows the mechanical properties of the Al and Alporas. Details of mechanical response of the monolithic Alporas under different loading conditions have been described extensively elsewhere[5, 7, 9–10, 16–18].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Elastic modulus/MPa</th>
<th>Poisson’s ratio</th>
<th>Yield strength/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHPA</td>
<td>69</td>
<td>0.33</td>
<td>110</td>
</tr>
<tr>
<td>Alporas</td>
<td>1.0</td>
<td>0.325</td>
<td>1.2</td>
</tr>
</tbody>
</table>

2.3 Monolithic bending particular

Four-point monolithic bending tests were conducted on an Instron testing machine at a constant rate of 1 mm/min. The inner and outer spans are 25 mm and 100 mm in the four-point bending, respectively. Beams were deformed until the core could not afford any loads, namely, cracks have been across the whole length of the core. The loading-deflection curves were recorded as the base data to be substituted into FEM analysis. During bending test, the deformation and failure process of sandwich and multilayer beams were monitored by a digital camera in-situ under some loads or deflections, which corresponds to significant deformation or damage of beams. These observations are used to compare and validate FEM modeling.

3 Results

3.1 Typical loading—deflection curves of beams under monolithic bending

There are two typical kinds of loading—deflection curves in the four beams. For type I, as shown in Fig.3, the bending load decreases after reaching the peak and then usually remains at about 90% of the peak value (sandwich $A_{c}\cdot c_{2r}t_{0}$) or even beyond the peak value at larger deflections (multilayer $A_{c}\cdot c_{2r}t_{0}$). This loading—deflection curve is similar to the compressive response of the monolithic foam[1–2], which means that indentation characteristic in a deformed beam, related to the localized deformation or densification, may present. For type II, the bending load decreases quickly after reaching the peak value and stabilizes at about 60% of the peak load until collapse of beams (sandwich $A_{c}\cdot c_{2r}t_{1}$ and multilayer $A_{c}\cdot c_{1r}t_{1}$). In this case, cracks may initiate at the stage of load decreasing and...
then propagate in the foam core during further deformation, which corresponds to severe damage of the core. The foam core thus loses the ability of bearing load. It is believed that in the stable stage of the type II the face sheets of the beam carry most of the load; as a medium, the foam core may simply transfer the load from the top face sheet to the bottom one.

Fig.3 Flexure loading—deflection curves of four designed sandwich and multilayer beams

In general, the different loading—deflection curves represent the typical deformation and failure modes of different beams, respectively. Details of each failure mode are discussed in the later sections. Here, significant loads or deflections, such as peak load or larger deflection applied onto the inner rollers (see Fig.2) that correspond to important deformation or damage characteristic are taken for FEM analysis. FEM modeling relative to the strain maps will reveal the mechanics mechanism causing different failure modes of sandwich and then multilayer beams.

3.2 FEM modeling of multilayer beams with 2 foam cores

3.2.1 Multilayer A₁-2A₉-c₁₁₀-t₀.5

Figure 4 displays the simulated deformation and strain distributions of the multilayer A₁-2A₉-c₁₁₀-t₀.5. Referring to Fig.4(a), upon application of the experimental peak load of 1 034 N, significant compressive strain concentration, $\varepsilon_{yy}$, ranging up to 5.5%, can be observed in the areas directly beneath and above the inner and outer points respectively. This indicates that indentation, the localized compression of the face sheet together with the adjacent core materials, might take place on the sample at the places where the loading rollers are touched. Under this load, more than 3% shear strain $\varepsilon_{xy}$, as shown in Fig.4(c), reveals that shear deformation of the core in the zone between inner and outer loading rollers also occurs. It points out that failure of this beam is most likely to showing mixed indentation mode (ID) + core shearing mode (CS), while ID is dominant. This is to say, in generally, the zones of the core around the inner or outer rollers are the most promising places for damage, due to the larger normal and shear strains here.

The actual deformation extent of the foam core in different areas of this sample, described by the equivalent strain, $\varepsilon_e$, is illustrated in Fig.4(d).

As shown in Fig.5, significant deformation of the core is simulated when a deflection value of 10 mm is applied. Strains are still in advance of at the places where each strain has the highest value in Fig.4. Severe deformations have taken place on the location with the highest strain, i.e., the core between the inner or outer rollers. It is found that circular holes (stands for cells in the actual foam) in the middle lines of the top and the bottom cores have been compressed and sheared into a contorted shape. In these places fracture of core happens.

Fig.4 Deformation and strain distributions of multilayer A₁-2A₉-c₁₁₀-t₀.5 at peak bending load of 1 034 N: (a) $\varepsilon_{yy}$; (b) $\varepsilon_{xx}$; (c) $\varepsilon_{xy}$; (d) Equivalent strain $\varepsilon_e$
because the plastic strains are far beyond the strain limitation of the cell well. It seems that at the final stage of bending, collapse of the sample was controlled by CS mode. Therefore, indentation at the initial stage of the deformation coupled with core shear at the final stage of the damage is the entire failure mechanism, which occurs to this multilayer model.

3.2.2 Multilayer $A_L-2A_F-c_{10-t_0.5}$

In this case, thickness of the face sheets is twice that of the multilayer $A_L-2A_F-c_{10-t_0.5}$. Thicker face sheets with higher stiffness than the thinner one could result in some different maps of strains in the core. The experimental flexure peak load of 1 640 N and a deflection of 6 mm are applied to this multilayer model and the simulations are presented as following.

At the peak load of 1 640 N, as observed in Fig.6, the normal strains, $\varepsilon_{yy}$ and $\varepsilon_{xx}$, are more evenly distributed as compared to the deformed multilayer model $A_L-2A_F-c_{10-t_0.5}$ shown in Fig.4, though very small zone with a concentration of compressive strain can be seen among the materials adjacent to the outer rollers. The 1.0 mm-face sheet thus can provide a better stiffness as compared to the 0.5 mm-face sheet. Hence, indentation is quite unlikely to take place in this model. However, the circular holes located in the middle lines of the top and bottom cores have more than 20% shear strain and about 4%–8% equivalent strains, as shown in Figs.6(c) and (d), respectively. This means that core shear is likely the dominant failure mode of this sample.

Figure 7 shows the simulated deformed model when a displacement of 6 mm is applied onto the model. This displacement is taken after the peak bending load is achieved, as seen in Fig.3. It is clear that the deformation is greater than that of the simulated model shown in Fig.6. The holes located in the middle lines of the top and bottom cores are distorted to a considerable degree. The shear strain, $\varepsilon_{xy}$, and the equivalent strain, $\varepsilon_e$, of 15%–30% (see Figs.7(c) and (d)) reveal severe deformation and damage concentrated in these areas in shear pattern. The normal strains, as shown in Figs.7(a) and (b), are still evenly. Hence, core shear is likely the exclusive failure mechanism in this model.

3.3 FEM modeling of sandwiches with single foam core

3.3.1 Sandwich $A_L-A_F-c_{20-t_0.5}$

In multilayer beams, the middle face sheet bears and transfers load and displacement are uniform from the top to bottom due to the fact that the middle sheet is much stiffer than that of the foam core, and this can be used to reinforce against the localized deformation. The foam core below the middle sheet is subjected to a uniform deformation along the length of the beam through the middle sheet. As for the single core sandwich, however, the deformation is transferred continuously from the top side to the bottom side of the sandwich, but no middle face sheet adjusts the homogenous distribution of deformation throughout the whole sheet. Even so, the deformation characteristic within the core of the single core sandwich may still exhibit a similar pattern to that of the top or bottom core and face sheet in the multilayer beam.

The deformation patterns of the sandwich $A_L-A_F-c_{20-t_0.5}$ at a deflection of 3.5 mm are displayed in Fig.8. As observed in Fig.8(a), the normal strain, $\varepsilon_{yy}$, around the inner and outer rollers is negative and considerably
Fig. 6 Deformation and strain distributions of multilayer $A_L-2A_F-C_{10}-t_1$ at peak bending load of 1,640 N: (a) $\varepsilon_{yy}$; (b) $\varepsilon_{xx}$; (c) $\varepsilon_{xy}$; (d) $\varepsilon_e$

Fig. 7 Deformation and strain distributions of multilayer $A_L-2A_F-C_{10}-t_1$ at deflection of 6 mm: (a) $\varepsilon_{yy}$; (b) $\varepsilon_{xx}$; (c) $\varepsilon_{xy}$; (d) $\varepsilon_e$

Fig. 8 Deformation and strain distributions of sandwich $A_L-A_F-C_{20}-t_0.5$ at deflection of 3.5 mm: (a) $\varepsilon_{yy}$; (b) $\varepsilon_{xx}$; (c) $\varepsilon_{xy}$; (d) $\varepsilon_e$
higher than that in the other zones. The $\varepsilon_{yy}$ reaches the highest value of about 8.5%, which means that the model has experienced compression in these particular areas of the model. In the other zones apart from the inner and outer rollers, $\varepsilon_{yy}$ is very smaller. Hence, the materials directly beneath and above the inner and outer rollers, are likely to experience localized compression, i.e., indentation, which dominates the failure of the sandwich $A_L$-$A_F$-$c_{20}$-$t_{0.5}$. Evident concaves on the face sheets adjacent to the inner or outer rollers validate the characteristic of the normal strain, $\varepsilon_{yy}$. Besides the concentrated compression, the zone in the core apart from the rollers is suffered from 6% shear strain (see Fig.8(c)), while the equivalent strain is ranging from 3% to 6% (see Fig.8(d)). These strain characteristics indicate that the core between the inner and outer rollers may deform in shear mode. It is confessedly that the strain distributions are stable due to no change of the loading pattern during monolithic bending. The final failure is composed of ID mode around the inner or outer rollers and CS mode on the core between the inner and outer rollers.

3.3.2 Sandwich $A_L$-$A_F$-$c_{20}$-$t_{1}$

Figure 9 shows the deformation behavior of the sandwich $A_L$-$A_F$-$c_{20}$-$t_{1}$ at a deflection of 5 mm. It is found that the normal strains, $\varepsilon_{yy}$ and $\varepsilon_{xx}$, as seen in Figs.9(a) and 9(b), are also evenly distributed, though a very small zone with a concentration of compressive strain can be seen in the core adjacent to the outer rollers. However, the thicker face sheet is stiffer, thus lowers the possibility of indentation on the core above the outer rollers. Instead, the shear strain, $\varepsilon_{xy}$ (see Fig.9(c)) and the equivalent strain, $\varepsilon_e$ (see Fig.9(d)) are much higher in the core between the inner and outer rollers, where the holes are severely distorted and tore. According to the deformation of the holes and shear strain distribution, it is believe that the plastic collapse by core shear could take place in this sandwich.

3.4 Observations on deformation and failure process of sandwiches

3.4.1 Indentation mode (ID mode)

This section describes the actual deformation process of the foam core and face sheets in multilayer and sandwich systems by a series of digital images taken at significant loads and deflections. In a multilayer beam, the middle face sheet gives an added stiffness support to the top and bottom face sheets and the 2-core beams. Moreover, the presence of the middle face sheet will result in an anti-symmetrical deformation pattern of sandwich above and below the middle face sheet. The middle face sheet can also act as a crack arrester in which it impedes the propagation upon meeting the crack.

The deformation and failure process of the multilayer $A_L$-$2A_F$-$c_{10}$-$t_{0.5}$ is shows in Fig.10. At the peak loading of 1 034 N, as seen in Fig.10(b), localized compression takes place at the top and bottom face sheets adjacent to the inner and outer rollers, while the middle face sheet behaves bending. The localized curve on both end face sheets together with the adjacent core is indentation mode, where is corresponding to the maximum normal strain $\varepsilon_{yy}$ shown in Fig.4(a). The penetrated depths of four indentations are 1–2 mm. At a deflection of 8.5 mm, indentations are developed continuously and the penetrated depth of the indentation reaches 2–3 mm, as shown in Fig.10(c). When the beam collapsed at a deflection of 20 mm, the penetrated depth of indentation reaches 3 mm on the inner rollers and 5 mm on the outer rollers, while cracks appeared in the beam, as shown in Fig.10(d). One crack is in the top core near the left inner roller (A in Fig.10(d)); others are in the bottom core (B in Fig.10(d)). Cracks in accordance with the maximum shear strain region in Figs.4(c) and

![Fig.9 Deformation and strain distributions of sandwich $A_L$-$A_F$-$c_{20}$-$t_{1}$ at deflection of 5 mm: (a) $\varepsilon_{yy}$; (b) $\varepsilon_{xx}$; (c) $\varepsilon_{xy}$; (d) $\varepsilon_e$](image_url)
Fig. 10 Images of deformation process of multilayer A$_L$-2A$_F$-c$_{10}$-t$_{0.5}$: (a) Without load; (b) At peak loading of 1 034 N, indentation initiates; (c) At displacement of 10 mm, deformation of multilayer beam continues; (d) At displacement of 20 mm, multilayer beam failed ultimately by indentation of top and bottom face sheets.

5(c) confirm that shear strain dominates the final stage of collapse. These observations indicate the actual failure mechanism of the multilayer A$_L$-2A$_F$-c$_{10}$-t$_{0.5}$ with ID mode + CS mode following to the estimation of FEM analysis. Although different damage modes would exist in each core and also localized deformation would occur in both end face sheets; however, the face sheets deform entirely in the manner of plastic hinge to fit the bending of whole beam (see the solid points in Fig.10(d)). Under monolithic bending, the phenomenon of localized compression is outstanding in the multilayer A$_L$-2A$_F$-c$_{10}$-t$_{0.5}$. It is believed that indentation is related to the relative low stiffness of the face sheet. When local stresses beneath the inner rollers are beyond the compressive strength of core foam, the top face sheet would not be able to bear the concentrated loading introduced by the collapse of the foam to keep the whole topside of the beam bending uniformly. Thus, one can describe failure of beams having indentation as localized collapsing of parts of the foam core, fast fracture of the core in shear mode and plastic hinging of the face sheets.

Figure 11 shows the deformation and damage process of the sandwich A$_L$-A$_F$-c$_{20}$-t$_{0.5}$. At the peak load of 1 027 N, which corresponds to a deflection of 1.15 mm as referenced in Fig.3, the two inner rollers begin to penetrate into topside of the beam. The penetrated depth of indentation is about 0.4 mm, as seen in Fig. 11(b). Fig.11(c) shows the development of indentation up to 3 mm at a deflection of 6 mm. For further deflection to 18 mm, the penetrated depth of indentation remains at 4 mm. Instead, shear fracture has initiated in the core along 45° from the indentation zone (arrow A in Fig.11(d)), the shear crack then propagates at a fast rate within the core near to the interface (not debonding of interface) in the region close to the outer roller. It is thought that for further development of indentation, higher load is needed to deform more face sheet and core; however, the ligament of the core cannot bear this load and fails in the observed manner by shear stress before further indentation. It should be noted that even in the final collapse, the beam displays the behavior of fast shear crack growth, where the shear crack is initiated at indentation zone by accumulation of concentrated strain, and therefore ID mode dominates the damage of the sandwich A$_L$-A$_F$-c$_{20}$-t$_{0.5}$. These observations also prove the characteristic of the normal and shear strains simulated by FEM in Fig.8.

3.4.2 Core shear mode (CS mode)

As for the multilayer A$_L$-2A$_F$-c$_{10}$-t$_{1}$, failure is entirely by shearing of core material. Fig.12 shows a series of digital images taken during bending. Beam bends at the peak flexure loading of 1 640 N are shown in Fig.12(b). Cracks initiate on the each core between the inner and outer rollers at a deflection of 10 mm, where corresponds to the maximum shear strain simulated by FEM displayed in Figs.6(c) and 7(c). At a deflection of 18 mm, the cracks have grown towards the overhang and the beam collapses. In this case, phenomenon of indentation does not appear here, but the pure core shear mode dominates the failure. The face sheets, however, also deform in the manner of plastic hinge (see the solid points in Fig.12(d)).

Lastly, sandwich with 20 mm-core and 1.0 mm-face sheets (A$_L$-A$_F$-c$_{20}$-t$_{1}$) would experience core shearing. As shown in Fig.13(c), cracks initiate at areas between the inner and outer rollers at a deflection of 12 mm,
Fig.11 Images of deformation process of sandwich $A_1-A_2-C_{200}-t_0.5$: (a) Without load; (b) At peak loading of 1 027 N, indentation initiated; (c) At displacement of 6 mm, indentation continues; (d) At displacement of 17 mm, sandwich beam failed dominantly by indentation mode.

Fig.12 Images of deformation process of multilayer $A_1-2A_2-C_{100}-t_1$: (a) Without load; (b) At peak bending load of 1 640 N; (c) At displacement of 10 mm; (d) At displacement of 18 mm, deformation of the structure continued until it failed in core shear ultimately.

which has revealed the visible damage caused by shear strain (see Fig.9(c)). As the shearing continued at a greater displacement, the load bearing ability of the sandwich beam decreased gradually (refer to Fig.3). Ultimately, the cracks grow fastly towards the overhang at a deflection of 22 mm, to which corresponds to collapse of the sandwich, as shown in Fig.13(d).

By comparing FEM simulations (Figs.4–9) to damage observations (Figs.10–13) mentioned above, it is fortunate that the strain contour on the model of thicker cell wall has provided the qualitative information which is enough to describe the actual shear deformation behavior of the cell wall, even no local cell wall buckling profile, meanwhile, macro-deformation profile of the
single core sandwiches or 2-core multilayer beams simulated by FEM is fully consistent to the experimental results. All of these means that the FEM model currently employed is basically reasonable to describe the actual deformation and give the most dangerous sites for failure of different sandwich geometry, even the model is approximate and a little rough. However, the current FEM model is not the best and should be optimized further in order to provide the precision strain contour and the detail of local buckling on the cell wall together, in particular in the ID failure mode. This consistency between the FEM simulations and monolithic bending experiments has also been explained by the in-situ surface displacement analysis[16−18], where the failure mechanism of the beams with different structures has been proposed also.

4 Discussion

4.1 Failure criterion of sandwich and multilayer beams composed of foam core and metallic face sheets

In this investigation, failure of sandwich and multilayer beams with HHPA face sheets of 0.5 mm is dominated by indentation mode and those with face sheets of 1 mm by core shear mode. Apparently, sandwiches with face sheets of 1 mm are much stiffer than those with face sheets of 0.5 mm. The thicker face sheet has potential to be against the localized compressive deformation as compared with the thinner ones in beams. In fact, the failure mode of an actual sandwich is related to the structure of the beam and mechanical properties of the foam core and face sheet. A beam composed of thinner, lower strength face sheet and thicker core tends to failure in ID mode; contrarily, tendency of CS mode failure increases. In the early works[16−17], a criterion was proposed successfully to estimate the failure mode of beams with various thickness of core, and various stainless steel face sheets. The criterion depends on the competition between the collapse loading $F_{ID}$ of indentation and loading limit $F_{CS}$ of core shear. For a certain beam, if $F_{ID} < F_{CS}$, the ID mode appears; otherwise, CS mode dominates. The $F_{ID}$[22] and $F_{CS}$[23] are given respectively by

$$F_{ID} = 4t(\sigma_c Y, \sigma_f Y)^{1/2} \quad (1)$$

and

$$F_{CS} = (d + c)\tau_c Y \quad (2)$$

where $\sigma_c$ and $\sigma_f$ in Eq.(1) are the yield strengths of the core and face sheet, respectively; $t$ is thickness of the face sheet. In Eq.(2), $\tau_c$ is the shear strength of the core, $d$ and $c$ are thicknesses of the sandwich and core. It is clear from Eqs.(1) and (2) that decreasing in thickness of the face sheet may bring ID mode to the beam, while decreasing in thickness of whole beam thickness reduces the value of $F_{CS}$, i.e., promoting tendency of CS mode. The applicability of the failure criterion for beams designed in this work is discussed as following.

For the sandwich $A_L-A_L-C_{20}-t_0$, $F_{ID}$ and $F_{CS}$ can be obtained by substituting $\sigma_c Y=1.2$ MPa and $\tau_c Y=0.8$ MPa (mechanical properties of Alporas) and $\sigma_f Y=110$ MPa.
(the yield strength of HHPA) into Eqs.(1) and (2). The values of $F_{ID}$ and $F_{CS}$ are 23 N/mm and 32.4 N/mm, respectively. Obviously, the criterion predicts failure mode of the sandwich $A_t-A_t-c_{20}=t_{0.5}$ correctly. Other sandwiches also subscribe to this criterion, and the calculations of $F_{ID}$ and $F_{CS}$ are listed in Table 3. It seems that the middle face sheet can not change the failure mode due to indentation just relative to both end face sheets.

### Table 3 Comparison of $F_{ID}$ and $F_{CS}$ for two sandwiches

<table>
<thead>
<tr>
<th>Sandwich</th>
<th>$F_{ID}$(N·mm$^{-1}$)</th>
<th>$F_{CS}$(N·mm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_t-A_t-c_{20}=t_{0.5}$</td>
<td>23</td>
<td>32.8</td>
</tr>
<tr>
<td>$A_t-A_t-c_{20}=t_{1}$</td>
<td>46</td>
<td>33.6</td>
</tr>
</tbody>
</table>

In addition, researches[19–21] suggested that face yield is the third failure mode in sandwich beams. The maximum face bending stress for a given sandwich structure is calculated by formula[23]:

$$\sigma_{max} = F_p L/(4t(d + c)b)$$

where $F_p$ is the peak bending load in bending-deflection curve; $L$ is span of the outer rollers; $t$, $d$ and $c$ are as same as those in Eqs.(1) and (2). It is clear that bending stresses on the face sheets are much less than yield strength of the face sheets. For example, at the peak flexure loading of 1 350 N in the sandwich $A_t-A_t-c_{20}=t_{1}$, the maximum bending stress acting on the face sheet is 33 MPa, which is far lower than yield strength of the HHPA. Similar level of the maximum bending stress can also be obtained for the other sandwiches by calculating Eq.(3). The face sheets deform in “plastic hinge” to maintain deformation compatibility of the whole sandwiches during bending especially under large deflections, but not in full-face yield for the current designed sandwiches.

### 4.2 Effect of failure mode on bending deformation energy

With a low strength and stiffness compared with dense metal, monolithic foam is not suitable as a structure material to endure loading. As a core in sandwich or multilayer beam, however, foam aluminum may absorb deformation energy, in particular under impact and compressive loads, while the face sheet supplies the ability of the sandwich to bear outer loading for its higher stiffness compared with that of the foam. This is the purpose of the beam design concluding foam metal as core and dense metal as face sheet.

For a sandwich or multilayer beam, the ability for absorbing deformation energy depends on the deformation and failure mode. It can be pointed out that toughening mechanisms in a beam different with those of the monolithic face sheet or core are: 1) constraint of the core supplied by the strong face sheet, 2) crack propagation within the core, 3) localized compressive yield of the core with indented face sheet and 4) face sheet plastic hinge deformation. The constraint effect means that the strength of the core is increased by the adjacent strong face sheet[17, 24]. The increase in the strength of the core leads to the further promotion of the core in the ability of absorbing energy. The most significant difference in toughening between ID mode and CS mode is in mechanism (3). If a sandwich fails in ID mode, the localized compressive yield of the core and indented face sheet adjacent to the core may consume much more energy rather than those fail solely by CS mode. The localized compressive deformation makes the foam core densify gradually, and then, the dense foam core obtains much higher strength limitation compared with the original foam, which contributes to extra capacity to consuming deformation energy[1–2, 9–10, 16–17].

Effect of the failure mode on the bending deformation energy can be understood straightforward from Fig.3. With a single core, sandwich containing face sheets of 0.5 mm consumes less deformation energy than that with face sheets of 0.5 mm; even the former has a higher peak flexure loading. The higher peak loading of the former is achieved due to the thicker face sheets of 0.5 mm; however, the loading decreases dramatically after reaching the peak value, where exactly corresponds to the beginning of core shear damage, i.e., initiation of shear crack. After the crack initiation, the core cannot transfer the loading efficiently to support the face sheet enduring much more loading. Adversely, indentation restricts the deformation locally in a compressive manner in the sandwich with face sheets of 0.5 mm. Dense foam core with a densification characteristic supports the face sheet withstanding the loading ulteriorly, promising the load basically maintaining at a relative high level after reaching the peak loading value, as shown in Fig.3. The sandwich $A_t-A_t-c_{20}=t_{0.5}$ may absorb more deformation energy (defined as the area surrounded by the loading-deflection curve and the deflection axis) than the sandwich $A_t-A_t-c_{20}=t_{1}$.

The multilayer $A_t-2A_t-c_{10}=t_{0.5}$ shows a little higher energy absorbing ability than the sandwich $A_t-A_t-c_{20}=t_{0.5}$ by comparing their area surrounded by the loading-deflection curve and the deflection axis, even they have the same total thickness of core. In the former, as seen in Fig.3, four indentations increasing the bending loading after the first peak value, consume more energy, while two indentations of the latter absorb a little lower energy, as seen in Fig.10 and Fig.11. This is due to the fact that the middle face sheet acts as a bottom for both end face sheets. In addition, the middle face sheet may
also contribute to the absorbing of extra energy at some extent. The multilayer $A_1-2A_4-c_{10^3}$ has the largest energy absorbing ability, which is attributed to its total face sheet of 3 mm. In this case, the foam core is secondary contribution to the deformation energy. However, bending loading of the multilayer $A_1-2A_4-c_{10^3}$ just with total face sheet of 1.5 mm, is indeed; over that of the total 3 mm-face sheet, sandwich at deflection is larger than 10 mm, as shown in Fig.3. This also proves the enormous contribution of the indentation to the deformation energy absorption. A principle for the sandwich or multilayer beam design in the absorbing energy applications is proposed here, that is the designed beam to the best of ID failure tendency.

5 Conclusions

FEM and four-point bending tests have been used to investigate the failure mechanisms of beams composed of aluminum foam core and half-hard pure aluminum face sheets, the following conclusions are made:

1) In beam structures, indentation and core shear are the basic failure modes. The FEM simulations and four-point bending tests reveal that indentation happens on the beam surface and foam core adjacent to the inner and outer rollers, where corresponds to the maximum compressive strain $ε_{0y}$. Shear crack initiation results in core shear failure on the core between the inner and outer rollers, where the maximum shear strain exists.

2) Failure mode in a beam depends on which one of load limitation, $F_{ID}$ of indentation or $F_{CS}$ of core shear, which is smaller. If $F_{ID}<F_{CS}$, indentation dominates the failure of a beam. On the contrary, CS would take place. Face yield does not happen for bending stress that acted on the face sheet is much smaller than yield strength of the face sheet in this work.

3) Beams that fail in ID mode have a potential to absorbing more deformation energy.

References


