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Bending behavior of aluminum foam sandwich with 304 stainless steel face-sheet

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Abstract. To gain more knowledge of aluminum foam sandwich structure and promote the engineering application, aluminum foam sandwich consisting of 7050 matrix aluminum foam core and 304 stainless steel face-sheets was studied under three-point bending by WDW-T100 electronic universal tensile testing machine in this work. Results showed that when aluminum foam core was reinforced by 304 steel face-sheets, its load carrying capacity improved dramatically. The maximum load of AFS in three-point bending increased with the foam core density or face-sheet thickness monotonically. And also when foam core was reinforced by 304 steel panels, the energy absorption ability of foam came into play effectively. There was a clear plastic platform in the load-displacement curve of AFS in three-point bending. No crack of 304 steel happened in the present tests. Two collapse modes appeared, mode A comprised plastic hinge formation at the mid-span of the sandwich beam, with shear yielding of the core. Mode B consisted of plastic hinge formation both at mid-span and at the outer supports.

Keywords: composite materials; three-point bending; mechanical properties; failure mechanism

1. Introduction

As a new type of foam material, aluminum foam shows a bright prospect in different fields, such as automobile, transportation and architecture, for its light quality, energy absorption and other physical properties like acoustic absorption (Degischer and Kriszt 2002, Gibson and Ashby 1997, Banhart 2001, Baumeister and Banhart 1997). But the mechanical properties of the foam itself are not high enough for engineering use (Duarte *et al.* 2010a,b, Nammi *et al.* 2010a,b, Huang *et al*. 2012a,b). To improve the mechanical properties of aluminum foam, aluminum foam composites have been developed in recent years.

Aluminum foam sandwich (AFS) structure is one of the popular aluminum foam composites. By covering two face-sheets on both sides of the foam core, an efficient sandwich structure is obtained. The face-sheet material can be either traditional metal or non-metal. It was found that the face-sheet carried the axial load or resist against bending, whereas the foam core beard the shear deformation usually when static load was conducted (Zu *et al*.2012a,b). For this special loading distribution and deformation mode, AFS can be designed to suit various applications. But how to select suitable parameters, such as core density and thickness, face-sheet material and the connection method of face-sheet and foam core, is mostly based on the knowledge of mechanical properties and failure mechanisms of AFS.

In recent years, people have focused on the fabrication method, mechanical properties and failure mechanisms of AFS structure. According to Matsumoto *et al*. (2015a,b) friction stir incremental forming process for sheet metals was applied to form the surface of a closed-cell type aluminum foam. They have also studied the compressive properties of the new sandwich structure. Kabir *et al.* (2014a,b). have studied the bending response of beams consisting of thin foam cores and thin face sheets of low and high yield strength. Their results showed that additional to indentation, face yielding occurred when low-strength face sheets were used and core yielding occurred when strong face sheets were used. Liu *et al.* (2013), Xie *et al.* (2013). have studied the response of sandwich panels with aluminum foam core and mild steel face-sheets under blast loading to investigate the blast wave attenuation ability and the deformation mechanism of the AFS. The effect of core thickness on the deformation mechanism of an aluminum foam core/thermoplastic composite facing sandwich structure under 4-point bending was investigated by Styles *et al.* (2007a,b). and their results indicated that the core thickness affected the deformation mechanism significantly. In our previous study, the effects of foam core density and face-sheet thickness on the mechanical properties and deformation mechanisms of AFS with 6061 aluminum alloy were reported (Yan and Song 2016). Not only traditional metal materials were used as face-sheet of AFS, researchers have also drawn attention to non-metal materials like fibers for their excellent strength and light weight. Wang *et al.* (2016a,b) have studied on a new type of AFS, of which a layer of glass fiber was provided at the interface between the metal panel and the aluminum foam core in the composite structure and the results showed the new composite structure had an improved comprehensive performance compared with the traditional AFS. Sun *et al.* (2012a,b). studied on the AFS with carbon fiber face-sheets and short aramid-fiber reinforced glued interface.

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Table 1 Chemical Composition Limit of 7050 Aluminum Alloy (wt %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	others	Al
≤0.12	0.15	2.2	0.04	2.3	0.06	5.7~6.7	0.05	0.15	margin

Table2 Chemical Composition Limit of 304 stainless steel panel (wt %)

C	Mn	P	S	Si	Cr	Ni	N	Cu	others
<0.08	2.00	0.045	0.030	1.00	18.0~20.0	8.0~10.5	--	--	margin

It is well-known that the understanding of the behavior of sandwich structure requires a broad test program, which is time-consuming and expensive. Therefore, it is essential and economic to undertake corresponding numerical simulations or establish analytical models to predict the properties of sandwich structure under different conditions.

To establish a suitable analytical model for AFS to predict the indentation strength and the influence of the indenter size on it, Vodenitcharova *et al.* (2012a,b) have conducted a series of experiments to complete this task. The model presented by them provided a solution of the indentation problem at any point along the loading path, without been dependent on the previous loading history. D'Alessandro et al. 2014a,b established a new model for aluminum foam sandwich panels based on the experimental tests. To study the vibrational performances of AFS panels Qin *et al.* (2014a,b) have also investigated the quasi-static indentation behavior of sandwich beams with a metal foam core. An analytical model was developed to predict the large deflections of indentation of metal foam core sandwich beam subjected to a concentrated loading. There are some other studies focused on the analytical model establishment of indentation behavior of sandwich structure under different conditions and tried to establish analytical model for it (Xie *et al.* 2013a,b, Crupi *et al.* 2015a,b, Rajaneesh *et al.* 2012a,b, Li *et al*. 2016a,b). Dou *et al.* (2016a,b) studied the compression behavior and the effect of strain-rate on AFS by combing C++ and ANSYS/LS-DYNA software.

Based on the previous studies, it can be found that researchers are investigating the mechanical properties and deformation mechanisms of sandwich structures and trying to establish analytical or simulate models for this new composite material intensively. However, there still have not gotten a reliable and commonly used model for AFS yet. The reason for this is that the designability of AFS is flexible and the deformation mechanisms of AFS are complicated. It is far away from gaining semi-rational formulas or analytical models like the equations used in traditional metal materials for sandwich structures. And thus, more studies are needed to reveal the mechanisms of AFS and then complete this task. And also the thicknesses of the face-sheet panels in most of the studies were thick. Such face sheets enable the sandwich panels to withstand high-impact loads without skin failure but potentially less energy absorption. And also, when AFS is used as functional material, such as noise-reduction panel or used under bridges, it is no need for it to absorb high compact loading (Vodenitcharova *et al.* 2012a,b). For these reasons, AFS with thin face-sheet is a problem worth studying.

In the present work, bending tests were carried out on beams consisting of 304 stainless steel face-sheets and 7050 aluminum alloy matrix foam core. To reveal the effects of face-sheet thickness and foam core density on the mechanical properties and failure mechanism of AFS, three thicknesses of 304 panel and three densities of aluminum foam were selected. The thicknesses of 304 panels were 0.6 mm, 0.8 mm and 1.0 mm respectively. This may supply more information on aluminum foam sandwich reinforced by 304 steel.

2. Materials and method

2.1 Materials

The sandwich core used in this study was 7050 matrix closed-cell aluminum foams. The chemical composition limits of the matrix material were shown in table1. The density of 7050 aluminum alloy is 2.83 g/cm^3. Tensile strength, yield strength and hardness of matrix alloy are $490MPa$, $420MPa$, $135HB$ respectively by commercial supplied. To investigate the influence of aluminum foam density, three types of aluminum foams were employed with relative density of 0.49 g/cm^3, 0.60 g/cm^3, 0.73 g/cm^3.

The closed-cell aluminum alloy foams were fabricated by melt foaming method and the yield strength of foam cores were $4.23MPa$, $10.07MPa$, $10.47MPa$ respectively under compression load. In order to study the effect of face-sheet thickness on the sandwich structure, 304 stainless steel panels with thickness of 0.6 mm, 0.8 mm, 1.0 mm were chosen as face-sheets. The tensile strength of 304 is more than $520MPa$ and the yield strength is more than $205MPa$. The chemical composition limits of 304 stainless steel panel were shown in table2. E44 epoxy resin and 650 resin firming agent were selected as adhesive. E44 is a bisphenol

A type epoxy resin and 650 is polyamide resin.

The foam-only beams were cut from large as-received panels with the thickness of 15 mm to the required dimensions (150 mm × 30 mm) using wire cutting machine.

The 304 panels were cut to the same size as foam-only samples in length and width by wire cutting machine too. Both foam samples and 304 samples were degreased and abraded to ensure the glued quality. The degreasing process was accomplished by washing the 304 sheets and the foam beams by water, acetone and water in order. The abrading process was finished by rubbing the surfaces with sandpaper. In addition, the surfaces to be bonded were cleaned using a brush and cloth artificially. Aluminum foam specimens were dried in oven for 4 hours at the temperature of 120℃.

After the aluminum foam samples and the 304 face-sheet samples prepared well completely, they were bonded by using epoxy resin and its firming agent in the order of 304 sheet – aluminum foam – 304 sheet carefully. The epoxy resin and firming agent were blended at the mass ratio of 1:1 and 15% acetone was added into them to improve the liquidity and operability. The fabricated sandwich specimens were pressed by special tools to ensure the adhesive surfaces were touched closely and the adhesive film was solidified at temperature of 80℃ in the oven for 2 hours and then putted into room temperature space for more than 48 hours before tested.

2.2 Three-point bending test

Specimens were loaded in a three-point bending configuration as shown in Fig. 1 with WDW-T100 electronic universal tensile testing machine. Tests were carried out with span lengths, l, of 80 mm and the overhang distance beyond the outer support, H, was 35 mm. The indenter moved at rate of 2 mm /min to indent the specimen at the midpoint of the top face-sheet. Diameter of the indenter was 10 mm (*a*= 10 mm).Specimen was simply supported on two support pins with the diameter of 10 mm.

The loads, P, and the indenter displacements, S, were recorded by the computer connected to the WDW-T100 automatically. The thickness of aluminum core, c, was 15 mm and the total thickness of the specimen, d, was varied by the face-sheet thicknesses. All specimens were tested under the same condition. Photographs were taken to record the deformation of foam cores and both face sheets during tests.

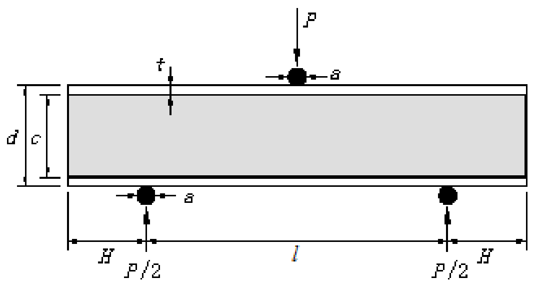


Fig. 1 sandwich beam under three-point bending

3. Results and discussion

3.1 Mechanical properties of AFS reinforced by 304 stainless steel face-sheets

As the aluminum foam sandwich structure investigated in this study consisted of aluminum foam core and 304 steel face-sheets, the density of the core and the thickness of the face-sheet may influence the mechanical properties and the deformation mechanism of the AFS. The reason for this is that when the thickness of foam core is decided, density decides its mechanical properties almost. Thickness of the face-sheet decided the strength of the skin. Thus, specimens consisting of different core densities and different face-sheet thickness were studied to reveal their effects.

Fig. 2 to Fig. 5 showed the load & displacement (P-S) curves of AFS in three-point bending to analyze the effects of aluminum foam density on the mechanical properties of aluminum foam sandwich structures. In each group the face-sheet thickness was the same while the foam core densities were different. As shown in Fig. 2, it is clear from the line graphs that the carrying capacity increased with the density of foam core in aluminum foam only beams. And also the bending rigidity increased with the density since the slope of P-S curve represents the rigidity to some extent.

The peak value of load increased from $0.66405kN$ to $0.82717kN$ when the foam density increased from 0.49 g/ cm^3 to 0.73 g/ cm^3. This indicates that the bending strength of pure aluminum foam increases with the density of foam material. This is related to the compression mechanism of aluminum foam. When aluminum foam is loaded under compressive load, cell edge and cell wall of the foams bear almost all the load. When the compressive stress exceeds the yield strength of cell edge or cell wall, the cell edge will be collapsed or the cell wall will be cracked. When foam density increased, cell diameter decreased and the wall thickness and edge improved, and thus the strength and stiffness of the foam enhanced.

When aluminum foam was enhanced by 304 steel panels, the effect of foam density was the same with that on the foam only beams. As shown in Figs. 3-5, AFS with 0.6 mm, 0.8 mm and 1.0 mm thickness of 304 steel skins, the maximum load increased with the density no matter what thickness of the 304 steel was. This is different from the result in our previous study (Yan and Song 2016), in which the face-sheets were 6061 aluminum alloy and the foam cores were the same with this study. This is related to the strength of face-sheet. The tensile strength and yield strength of 304 steel are much higher than 6061 alloy, and thus the loading capacities of 304 steel face-sheets are higher than 6061 alloy face-sheets. In the present study, when aluminum foam was enhanced by 304 steel panels, the loading capacity of face-sheet was higher than foam core. At the very beginning of loading, 304 steel face-sheets carried most of the load (upper layer carried compressive load and lower layer carried tensile load). The load spread to the foam core during loading. The face-sheets did not fail for their high strength while the foam core produced plastic deformation for its lower compressive strength. This is to say that in AFS with 304 steel face-sheets, foam core worked more efficiently. But in AFS with 6061 alloy face-sheets, load is consumed during the plastic deformation of the lower face-sheet, especially the thin ones.

From Fig. 3 to 5, it can be seen there were three stages during the three-point bending. At the first stage the load value briefly increased almost linearly with displacement until reached its peak value. This is the linear stage of AFS. And then the load value fluctuated with the increase of displacement. This is the special plastic stage due to the foam core, during which stage energy was absorbed. Finally, the load decreased quickly, the whole structure failed completely. The energy absorption value of each type of specimens can be calculated by the follow equation

$$W = P \cdot S = \int PdS \tag{1}$$

Where P refers to load and S refers to displacement. The upper limit of the integral was the end of the yield stage but not the end of each curve as the structure had invalided at the end of the yield stage completely. The lower limit of the integral was zero.

Fig. 6 showed the comparison value of the maximum load of AFS with foam core density of 0.49 g/cm^3, 0.60g/cm^3 and 0.73 g/cm^3 respectively to reveal the effects of foam core density on the maximum load of AFS clearly.

When aluminum foam core was reinforced by 304 steel face-sheets, the maximum load increased with the density.

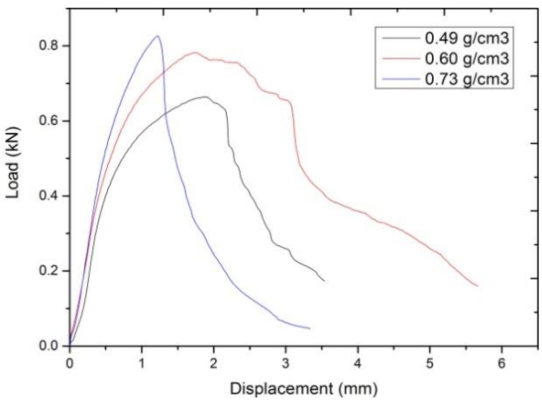


Fig. 2 Curve of P-S of foam only beams

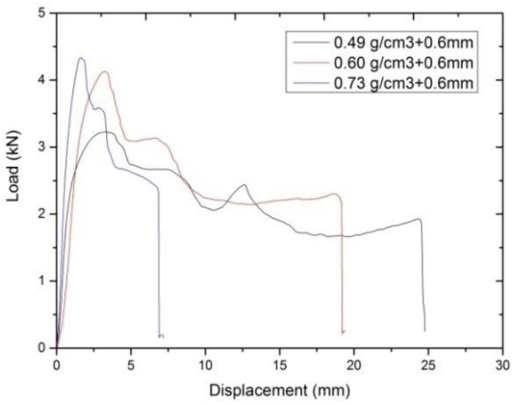


Fig. 3 Curve of P-S of AFS with face-sheets of 0.6 mm thickness

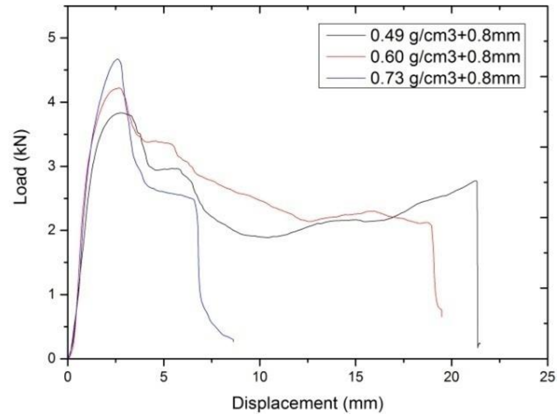


Fig. 4 Curve of P-S of AFS with face-sheets of 0.8 mm thickness

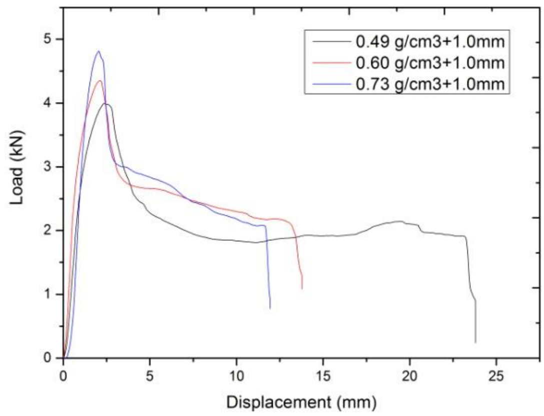


Fig. 5 Curve of P-S of AFS with face-sheets of 1.0 mm thickness

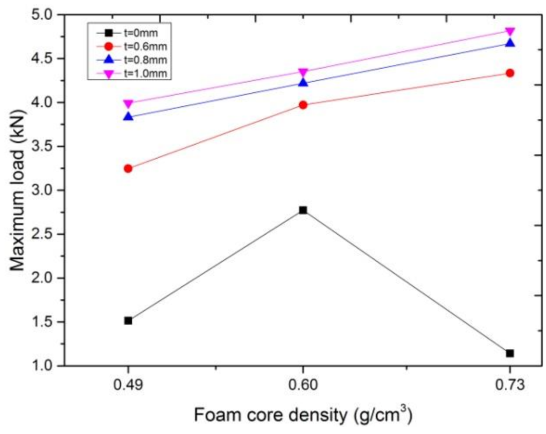


Fig. 6 Effects of foam core density on the maximum load of AFS

The detailed values were listed in Table 3. In other words, peak load is decided by foam core density to some extent. Fig. 7 showed the comparison value of energy absorption of AFS with foam core density of 0.49 g/cm^3, 0.60g/cm^3 and 0.73 g/cm^3 respectively to reveal the effects of foam core density on the energy absorption capacity of AFS. It is clear that the energy absorption value decreased with the increase of foam core density. When aluminum foam was enhanced by 304 steel panels as face-sheets, the foam core with lower density played its role more effectively than the high density foams. When the density of foam core decreased, its porosity increased, thus there was more room for deformation. Energy absorbed during the deformation process, and thus the energy absorption capacity increased with the decrease of density. This result is consistent with the result of Liu et al in reference (Liu *et al*. 2013a,b) and our previous study in reference (Yan and Song 2016). It should be noted that this phenomenon was performed when aluminum foam was reinforced by high strength metal face-sheets, but not in foam only beams. For foam only beams, load carrying ability plays main role.

Fig. 8 to Fig. 10 showed the P-S curves of AFS in three-point bending. The foam core density of the specimens in one group was the same while the face-sheet thickness was different. This is to study the effects of face-sheet thickness on the mechanical properties of AFS in three-point bending.

From Fig. 8, the 1.0 mm specimen sustained a maximum load six times that of the sample without face-sheet when foam core density was 0.49 g/cm^3. The detailed values were listed in Table 3. The peak load of AFS went up with the thickness of face-sheet in general. But the shape of the curves up to and following the peak load were a little different. The specimen with 1.0 mm thickness face-sheet demonstrates a high peak load at an increased displacement, then a significant load drop prior to reaching a plateau. But the plateaus for AFS with 0.8 mm and 0.6 mm thickness face-sheets were retarded. Same results can be gained from Figs. 9 and 10, even though the foam core densities were different. Because with the increase of face-sheet thickness, the whole strength of AFS structure improved, and thus the peak load carrying ability increased. This result is easier to be seen from Fig. 11. But the effect of face-sheets thickness on the energy absorption capacity was more completed than on load carrying capacity. As shown in Fig. 12, for foam core with density of 0.73 g/cm^3, energy absorption value of the AFS increased with the face-sheet thickness steadily. But for AFS with foam core density of 0.60 g/cm^3, energy absorption value went done when the 304 face-sheet thickness was more than 0.8 mm. For AFS with foam core density of 0.49 g/cm^3, the turning point came earlier than the former. It was happened when the 304 face-sheet thickness was 0.6 mm. For aluminum foam core with high density, its load carrying ability plays a more important role than its energy absorption ability in term of the properties of foam core itself. When foam core density was 0.73 g/cm^3, the load carrying ability was steady, whereas the porosity was low. And thus the energy absorption value of AFS increased with the face-sheet thickness because of the improvement of the strength of face-sheet and foam core. When foam core density decreased, its porosity increased and then the function of energy absorption ability improved gradually. Once foam core was reinforced by face-sheet, the high porosity one would have high energy absorption ability. From Fig. 12, it can be also found that the most matched parameters exist in aluminum foam sandwich structure.

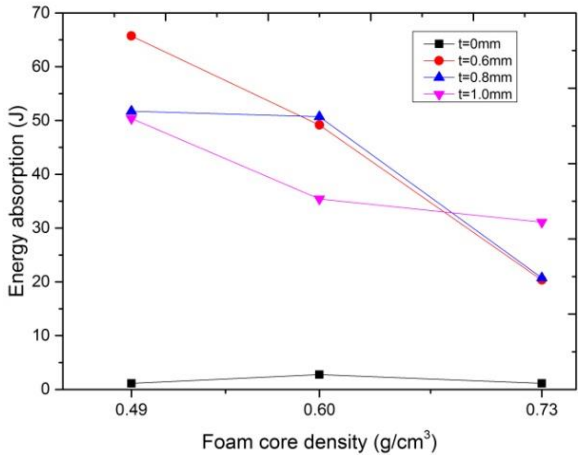


Fig. 7 Effects of foam core density on the energy absorption of AFS

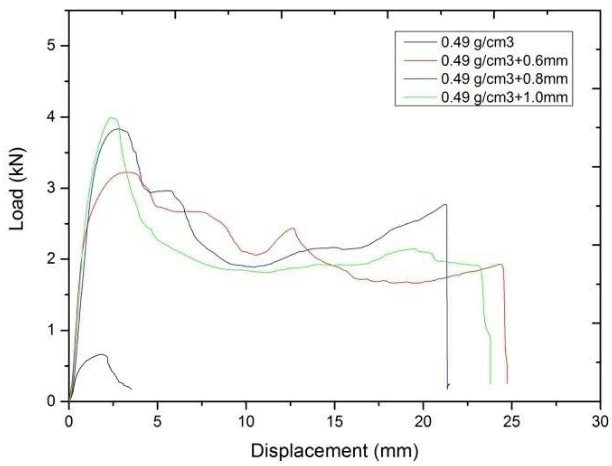


Fig. 8 Curve of P-S of AFS with the foam core density of 0.49 g/cm^3

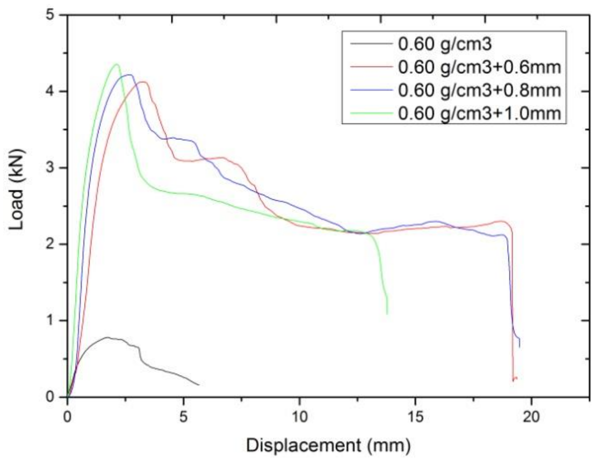


Fig. 9 Curve of P-S of AFS with the foam core density of 0.69 g/cm^3

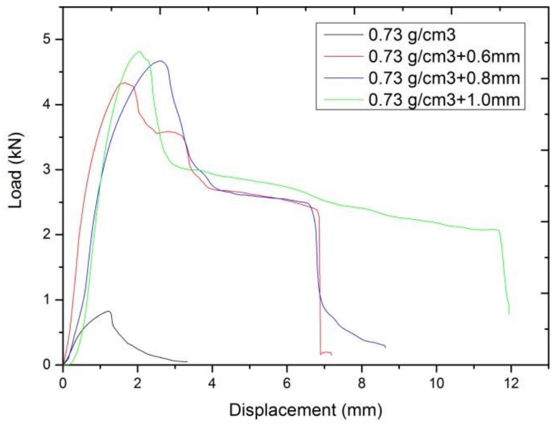


Fig. 10 Curve of P-S of AFS with the foam core density of 0.73 g/cm^3

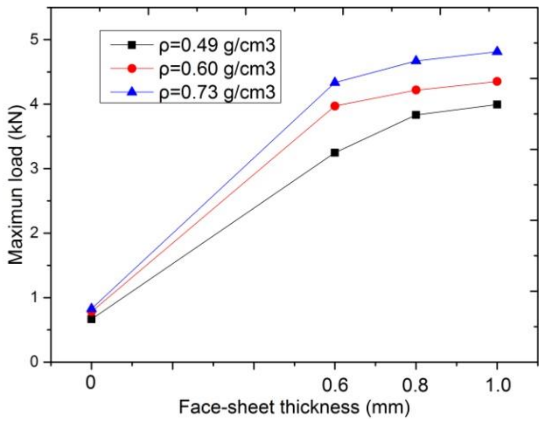


Fig. 11 Effects of face-sheet thickness on the maximum load of AFS

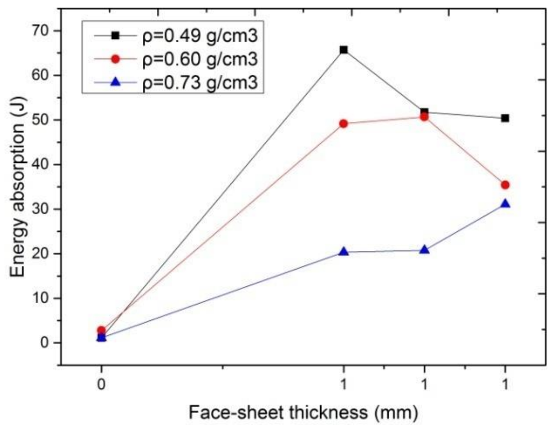


Fig. 12 Effects of face-sheet thickness on the energy absorption of AFS

In general, the maximum load increased with foam core density or face-sheets thickness monotonically, the energy absorption value was decided by the combined action of foam core density and 304 face-sheets. It is necessary to make an optimal thickness ratio of panel to core for the AFS to obtain high specific bending behavior to meet different usage.

Table 3 Peak load, displacement and energy absorption of each specime

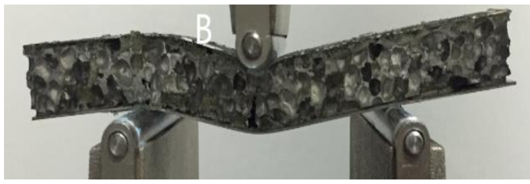
Properties / Types of AFS	Maximum load (kN)	Displacement at maximum load (mm)	Energy absorption in total (J)
0.49 g/cm^3 foam	0.664	1.886	1.515
0.60 g/cm^3 foam	0.782	1.736	2.771
0.73 g/cm^3 foam	0.827	1.219	1.142
0.49 g/cm^{3}foam+0.6 mm steel face-sheets	3.225	3.288	53.465
0.60 g/cm^{3}foam+0.6 mm steel face-sheets	3.971	3.250	49.174
0.73 g/cm^{3}foam+0.6 mm steel face-sheets	4.334	1.661	20.340
0.49g/cm^{3}foam+0.8mm steel face-sheets	3.832	2.790	51.741
0.60 g/cm^{3}foam+0.8 mm steel face-sheets	4.218	2.656	50.689
0.73 g/cm^{3}foam+0.8 mm steel face-sheets	4.670	2.611	20.760
0.49 g/cm^{3}foam+1.0 mm steel face-sheets	3.994	2.358	50.378
0.60 g/cm^{3}foam+1.0 mm steel face-sheets	4.352	2.091	35.425
0.73 g/cm^{3}foam+1.0 mm steel face-sheets	4.814	2.045	31.105

3.2 Failure mechanism of AFS reinforced by 304 stainless steel face-sheets

Load carrying capacity and energy absorption capacity are both decided by the failure mechanism of AFS. The variation tendency of P-S curves of AFS is in accord with the deformation of the specimens. Fig. 13 showed the deformation progress of a sample and its P-S curve. 13-1 was the initial state of the sample in three-point bending. With the increase of the displacement loading, the sample deformed gradually. Elastic deformation happened from 13-1 to 13-3 until the first crack point A appeared. This stage is corresponding with the interval between O and A in the P-S curve of 13-7. During which, AFS worked as an entirety. After that, plastic deformation began. A and B were both plastic hinges of the AFS beam in three-point bending. As the indenter moved, the second plastic hinge B in picture 13-4 appeared. After then foam core collapsed until the foams between A and B cracked completely. This stage is in accord with the interval between B and C in picture 13-7.

This is also the most significant deformation stage for AFS, during which energy was absorbed. When the plastic hinge extended from B to C, the beam failed completely under three-point bending.

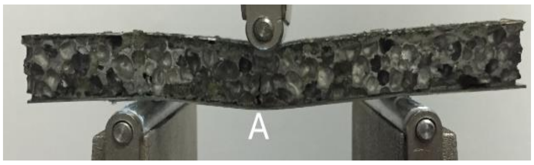
13-1



13-4

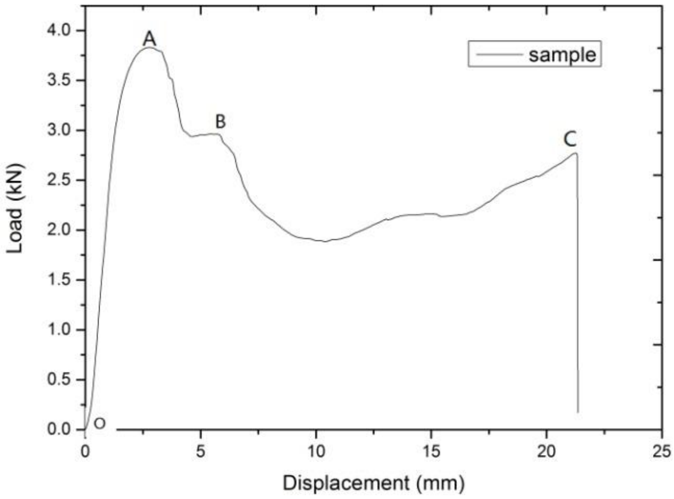
13-2

13-5



13-3

13-6



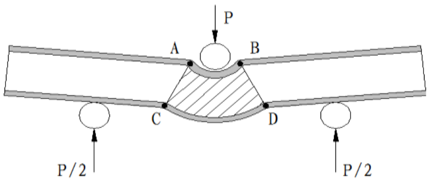
13-7

Fig. 13 Deformation of a sample and its P-S curve

There were two collapse modes in the present study as shown in Fig. 14. The pictures (Figs. 14(a)-14(c)) were the states of the specimens after tested in the present work and the pictures (Figs. 14(d)-14(f)) were the analytical models correspondingly. When a sandwich beam is subjected to a transverse shear force the shear force is carried mainly by the core, and the plastic collapse by core shear can result. Mode A comprises plastic hinge formation at the mid-span of the sandwich beam, with shear yielding of the core. Mode B consists of plastic hinge formation both at mid-span and at the outer supports. This is corresponding to the result of Ashby et al. (Ashby *et al.* 2000a,b). The collapse modes appeared in this study are dependent neither on the face-sheet thickness nor on the foam core density, but may be related to the span and the overhang distances of the specimens. The relationships need more study to interpret. A, B, C, D, E and F in Figs. 14(d)-14(f) are plastic hinges.

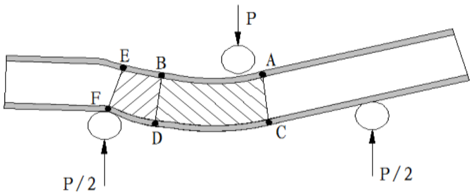
In the present study, almost all of the specimens failed by the collapse of the foam core, several specimens failed by the failure of the adhesive interface. There was no lower layer 304 steel face-sheet cracked, because the tensile strength of 304 steel is high enough to bear the bending strength. The bending load can be dispersed into the foam core and transformed in the plastic hinge field. This indicates that when aluminum foam core is reinforced by considerable high strength face-sheet, the foam core comes into play more effectively. According to Plantema *et al*. (Allen 1969), a theoretical model was built by ignoring the strength of face-sheet and treated is as a thin plate. But in reality, the additional strength provided by face-sheet is non-negligible, even though the face-sheet is very thin. Other analytical models were built by different investigators to perfect the previous ones, but they still need tests and improvement (Ashby *et al.* 2000a,b).

(a) Mode A



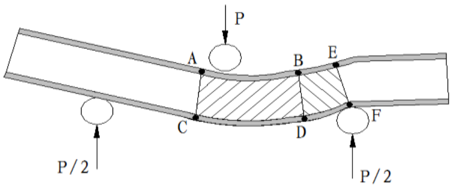
(d) Mode A*

(b) Mode B1



(e) Mode B1*

(c) Mode B2



(f) Mode B2*

Fig. 14 Competing collapse modes for core shear of sandwich beams in three-point bending

4. Conclusions

Aluminum foam sandwich with 7050 matrix aluminum foam core reinforced by 304 steel face-sheets was studied in this work. The effects of foam core density and face-sheet thickness on the load carrying capacity and energy absorption capacity of AFS were studied systematically. And also the failure mechanism of AFS under three-point bending was researched. The main conclusions can be drawn as follows.

- When aluminum foam was reinforced by 304 steel face-sheets, its load carrying capacity improved with the increase of either foam core density or face-sheet thickness monotonically. The maximum peak load 4.814 kN was obtained in the AFS with 0.73 g/cm^3 foam core and 1.0 mm thickness of 304 steel face-sheets.
- Energy absorption capacity was mainly depended on the carrying capacity of aluminum foam when there were no 304 steel face-sheets. When the foam core was enhanced, the energy absorption capacity increased with the decrease of foam core density. In the present work, the highest energy absorption value 65.729J was belongs to the AFS with 0.49 g/cm^3 foam core and 0.6 mm thickness of 304 steel face-sheets.
- When aluminum foam core was reinforced by 304 steel panels, the foam core came into play effectively. The special energy absorption function of aluminum foam was used well.
- Two collapse modes appeared in the present study. Mode A comprised plastic hinge formation at the mid-span of the sandwich beam, with shear yielding of the core. Mode B consisted of plastic hinge formation both at mid-span and at the outer supports. Collapse mode is related to the dimension of the test, and also to the strength match of foam core and face-sheet. Further work is being done to build the relationship between them.

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References

Allen H. (1969), A*nalysis and design of structural sandwich panels,* Pergamom, Oxford.

Ashby, M.F., Evans, A.G., Fleck, N.A., Gibson, L.J., Hutchinson, J.W. and Wadley, H.N.G. (2000), *Metal Foams: A Design Guide*, Butterworth-Heinemann, Boston.

Banhart, J. (2001), “Manufacture characterisation and application of cellular metals and metal foams", *Prog. Mater. Sci.*, **46**(6), 559-632.

Baumeister, J., Banhart, M. and Weber, M. (1997), "Aluminum foams for transport industry", *Mater. Des*., **18**(4-6), 217-220.

Crupi, V., Kara, E., Epasto, G., Guglielmino, E. and Aykul, H. (2015), "Prediction model for the impact response of glass fibre reinforced aluminum foam sandwiches", *Int. J. Impact Eng*., **77**, 97-107.

D'Alessandro, V., Petrone, G., De Rosa, S. and Franco, F. (2014), "Modelling of aluminum foam sandwich panels", *Smart Struct. Syst*., **13**(4), 615-636.

Degischer, H. and Kriszt, B. (2002), *Handbook of cellular metals: production, processing, application*, In: Cambridge solid state science series, Wiley-VCH Verlag BmbH & Co. KGaA.

Dou, R., Qiu, S., Ju, Y. and Hu, Y. (2016), "Simulation of compression behavior and strain-rate effect for aluminum foam sandwich panels", *Comput. Mater. Sci*., **112**, 205-209.

Duarte, I., Vesenjak, M. and Krstulović-Opara, L. (2014), "Variation of quasi-static and dynamic compressive properties in a single aluminum foam block", *Mater. Sci. Eng*., **616**, 171-182.

Gibson, L.J. and Ashby, M.F. (1999), *Cellular solids: structure and properties* (2nd Editon), Cambridge University Press, Cambridge.

Huang, L., Wang, H., Yang, D.H., Ye, F. and Lu, Z.P. (2012), "Effects of scandium additions on mechanical properties of cellular Al-based foams", *Intermetallics*, **28**, 71-76.

Kabir, K., Vodenitcharova, T. and Hoffman, M. (2015), "Response of aluminum foam-cored sandwich panels to bending load", *Compos. Part B*, **64**, 24-32.

Li, Z., Chen, X., Jiang, B. and Lu, F. (2016), "Local indentation of aluminum foam core sandwich beams at elevated temperatures", *Compos. Struct*., **145**,142-148.

Liu, H., Cao, Z.K., Yao, G.C., Luo, H.J. and Zu, G.Y. (2013), "Performance of aluminum foam-steel panel sandwich composites subjected to blast loading", *Mater. Des*., **47**, 483-488.

Matsumotoa, R., Tsuruokaa, H., Otsub, M. and Utsunomiya, H. (2015), "Fabrication of skin layer on aluminum foam surface by friction stirincremental forming and its mechanical properties", *J. Mater. Process. Tech*., **218**, 23-31.

Nammi, S.K., Myler, P. and Edwards, G. (2010), "Finite element analysis of closed-cell aluminum foam under quasi-static loading", *Mater. Des*., **31**(2), 712-722.

Plantema, F. (1996), *Sandwich construction*, Wiley, New York.

Qin, Q., Zhang, J., Wang, Z., Li, H. and Guo, D. (2014), "Indentation of sandwich beams with metal foam core", *T. Nonferr. Metal. Soc. China*, **24**(8), 2440-2446.

Rajaneesh, A., Sridhar, I. and Rajendran, S. (2012), "Impact modeling of foam cored sandwich plates with ductile or brittle faceplates", *Compos. Struct*., **94**(5), 1745-1754.

Styles, M., Compston, P. and Kalyanasundaram, S. (2007), "The effect of core thickness on the flexural behavior of aluminum foam sandwich structures", *Compos. Struct*., **80**, 532-538.

Sun, Z., Jeyaraman, J., Sun, S., Hu, X. and Chen, H. (2012), "Carbon-fiber aluminum-foam sandwich with short aramid-fiber interfacial toughening", *Compos.: Part A*, **43**(11), 2059-2064.

Vodenitcharova, T., Kabir, K. and Hoffman, M. (2012), "Indentation of metallic foam core sandwich panels with soft aluminium face sheets", *Mater. Sci. Eng*., **558**, 175-185.

Wang, N., Xiang, C., Ao, L., Li, Y., Zhang, H. and Liu, Y. (2016), "Three-point bending performance of a new aluminum foam composite structure", *T. Nonferr. Metal. Soc. China*, **26**(2), 359-368.

Xie, Z., Zheng, Z. and Yu, J. (2013), "Localized indentation of sandwich panels with metallic foam core: Analytical models for two types of indenters", *Compos.: Part B*, **44**(1), 212-217.

Yan, C. and Song, X. (2016), "Effects of foam core density and face-sheet thickness on the mechanical properties of aluminum foam sandwich", *Steel Compos. Struct*., **21**(5), 1145-1156.

Zu, G., Song, B., Zhong, Z., Li, X., Mu, Y. and Yao, G. (2012), "Static three-point bending behavior of aluminum foam sandwich", *J. Alloy. Compd*., **540**, 275-278.

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