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Effects of face-sheet materials on the flexural behavior of aluminum foam sandwich

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Abstract. Properties of AFS vary with the changes in the face-sheet materials. Hence, the performance of AFS can be optimized by selecting face-sheet materials. In this work, three types of face-sheet materials representing elastic-perfectly plastic, elastic-plastic strain hardening and purely elastic materials were employed to study their effects on the flexural behavior and failure mechanism of AFS systematically. Result showed face-sheet materials affected the failure mechanism and energy absorption ability of AFS significantly. When the foam cores were sandwiched by aluminum alloy 6061, the AFS failed by face-sheet yielding and crack without collapse of the foam core, there was no clear plastic platform in the Load-Displacement curve. When the foam cores were sandwiched by stainless steel 304 and carbon fiber fabric, there were no face-sheet crack and the sandwich structure failed by core shear and collapse, plastic platform appeared. Energy absorption abilities of steel and carbon fiber reinforced AFS were much higher than aluminum alloy reinforced one. Carbon fiber was suggested as the best choice for AFS for its light weight and high performance. The versus strength ratio of face sheet to core was suggested to be a significant value for AFS structure design which may determine the failure mechanism of a certain AFS structure.

Keywords: aluminum foam sandwich; composite structure; quasi-static bending; failure mechanism; energy absorption

1. Introduction

Aluminum foam sandwich (AFS), making of aluminum foam core and metal or non-metal face-sheet, has attracted lots of attention in recent years for its light weight, energy absorption and sound insulation ability (Lu and Yu 2003, Ashby *et al*. 2000, Gibson and Ashby 1997). For the light weight advantage, it is suitable to be used in aviation, aerospace and ship fields (Crupi *et al*. 2013, Hao *et al*. 2015). And also it has a wide use in many protective engineering as shock-resistance components and energy absorbers to resist in blast, shock or impact loads attributing to its energy absorption ability (Jing *et al*. 2013, Li *et al*. 2016). Beyond these, there are still a lot of potential applications of AFS waiting for exploitation. Research of AFS continues to be of academic and industrial interests consequently. AFS is not only a kind of material, but also can be regarded as a type of structure. As a structure, it is devisable, which means the sandwich cores, face-sheet materials and other geometric parameters of AFS are all elective. The diversity of the structure makes its mechanical properties differed and failure mechanism complicated.

Over the past decade, a large number of studies on aluminum foam sandwich have been widely reported and published focusing on its preparation method, mechanical and physical properties and so on (Styles *et al*. 2007, Guo *et al*. 2013b, Wang *et al*. 2015, Kabir *et al*. 2014, Steeves and Fleck 2004, Xu *et al*. 2014, Rajaneesh *et al*. 2014). By four-point bending test, the flexural behavior of AFS consisting of closed-cell aluminum foam core and glass-fiber/polypropylene preprg face-sheets was studied to figure out the effect of foam core thickness on their mechanical properties and failure modes. Results showed a number of failure mechanisms between the different core thicknesses (Styles *et al*. 2007). According to Zu *et al*. (2013). Aluminum foam was sandwiched by Q235B steel and the effects of face-sheet and foam core thickness were investigated by static three-point bending test. Wang *et al*. (2015) prepared AFS by powder pack roll melting process, whose face sheet is 1060 pure aluminum, the result indicated the thickness of face sheet and core was an import geometry parameter for aluminum foam sandwich, which was related to the failure mode of aluminum foam sandwich. Not only thickness of foam core and face-sheet panels influences the failure mechanism and the mechanical properties of aluminum foam sandwich, but also the face-sheet materials. Kaveh Kabir and his co-authors (2014) studied on the AFS consisting of ALPORAS foam and aluminum alloy face-sheet. To investigate the influence of the yield strength of the face-sheet, two types of aluminum alloys were chosen: (i) AA 1100-Owith low yield strength; and (ii) AA 3104-H19 with high yield strength. Result showed yield strength of the face-sheet influenced the failure mechanism of the AFS structure: face yielding occurred when low-strength face sheets were utilised and core yielding occurs when strong face sheets were used. In addition to flexure loading, AFS is widely used to with stand impact and blast loading, so the behavior of AFS

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under these kind of loading types are also worth studying (Mohan *et al*. 2011, Han and Cho 2014, Cheng *et al*. 2015, Aldoshan and Khanna 2017, Liu *et al*. 2017). Mohan *et al.* (2011) studied on the impact response of aluminum foam sandwich structures reinforced by different face-sheet materials by drop impact test. The influence of thickness of foam core on the energy absorption and deformation was studied at the same time. Han and Cho (2014) have also studied on the impact behavior of AFS by experiment and simulation analysis. The face sheet used in their work was Al-3003.

From the previous studies, it can be seen that there are lots of collocations for AFS structure and the selection of the materials and parameters all make a big difference on its strength and failure mechanism. In most of the studies, only one type of materials is chosen to fabricate AFS and then investigate the effects of face-sheet thickness or the foam core density or other factors, but rare works study on the AFS making of different materials systematically, even though the behavior of AFS with different face-sheet materials differed from each other significantly. More studies about the effects of face-sheet materials on the properties of AFS are necessary to provide more scientific information and foundation to guide the engineering design and application of AFS.

In the present work, three types of face-sheet materials are selected to fabricate aluminum foam sandwich to study the influence of face-sheet materials on the mechanical properties and failure mechanism of aluminum foam sandwich structures. The materials are aluminum alloy 6061, stainless steel 304 and carbon fiber fabric respectively. The specimens are made by gluing method and tested by using WDW-100 electronic universal tensile testing machine under three-point bending condition. The effects of face-sheet materials on the flexural strength and deformation of AFS were analyzed. An important value which decides the failure mechanism and energy absorption capacity of AFS was discussed.

2. Materials and method

2.1 Materials

Closed-cell aluminum foam with 7050 matrix is selected as sandwich core as it is of well-distributed inner bubbles and high overall strength. The foam materials were supplied by Su zhou jia shi de metal foam Co., Ltd. Density of the foam is 0.73 g/cm^3. The closed-cell aluminum alloy foam is fabricated by melt foaming method and the yield strength of foam cores is 10.47 MPa under compression load. This kind of foam is the most stable and homogenous in the factory which supplies material for the laboratory. The chemical composition limits of aluminum alloy 7050 were as shown in Table1.

Three types of face-sheet materials are considered in this study, they are aluminum alloy 6061 which represents the elastic-perfectly plastic materials, stainless steel 304 represents elastic-plastic strain hardening materials and purely elastic materials of carbon-fiber fabric (CFF). The mechanical properties of the face-sheet materials are listed in Table 2. The materials are all supplied by producers who have enough qualifications and the properties of the materials are all tested by professional test units. E44 epoxy resin and 650 resin firming agent produced by HUNAN BAXIONGDI NEW MATERIAL CO., LTD. are selected as adhesive. E44 is a bisphenolA type epoxy resin and 650 is polyamide resin.

2.2 Specimens

All the specimens were fabricated by gluing method manually. The foam was cut down from big as received panels to the designed size of 150 mm in length and 30 mm in width by using sawing machine. The thickness of the foam was 15 mm. The aluminum alloy 6061 panels were also cut to the right size by wire-electrode cutting to match the foam core. The thicknesses of 6061 were 0.8 mm and 1.0 mm. Stainless steel 304 panels were progressed by the same way as aluminum alloy 6061 and the size parameters were same to aluminum alloy 6061 too. Carbon-fiber fabric was cut by shear to the right size. The size of the cut fabric was a little bigger than the foam core to make sure the foam core can be covered completely. The extra carbon-fiber fabric was moved away carefully after the specimen was solidified perfectly. To gain good adhesion surface, the surfaces of face-sheet materials and foam core were degreased by acetone and water. The gluing surfaces were abraded carefully by sandpaper and cleaned by air pump to sweep the powder away.

After the foam core and face-sheet panels were prepared well completely, they were bonded by epoxy resin and its

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

Table 2 Mechanical properties of face-sheet materials

Properties face-sheet	Density	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
6061	2.91 g/cm^3	112	183	72
304	7.93 g/cm^3	206	521	201
CFF	298 g/m^2	--	3521	232

firming agent through wet lay-up method in the order of face-sheet – aluminum foam –face-sheet carefully. The carbon-fiber fabric samples were impregnated by epoxy resin adequately. The epoxy resin and firming agent were blended at the mass ratio of 1:1 before used. The fabricated sandwich specimens were pressed under a certain press force to ensure the adhesive surfaces were touched closely. After all the work was done, put the specimens in the oven at 80°C for 2hours for 6061 and 304 reinforced aluminum foam and 5 hours for CFF reinforced one, and then at room temperature more than 48 hours. AFS with carbon-fiber face-sheet was solidified for longer time since the adhesive between the layers were abundant.

2.3 Three-point bending test

In this work, three-point bending tests were conducted out through WDW-T100 electronic universal tensile testing machine. The test configuration was showed in Fig. 1 and the detailed parameters were listed out in Table 3. The value of face-sheet thickness t was varied by the thickness of face-sheet panels. To gain more credible result, more than five specimens for each group of AFS were tested under the same condition.

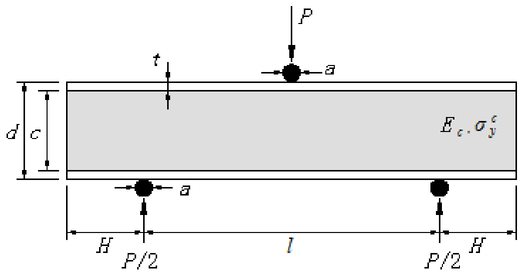


Fig. 1 Three-point bending test

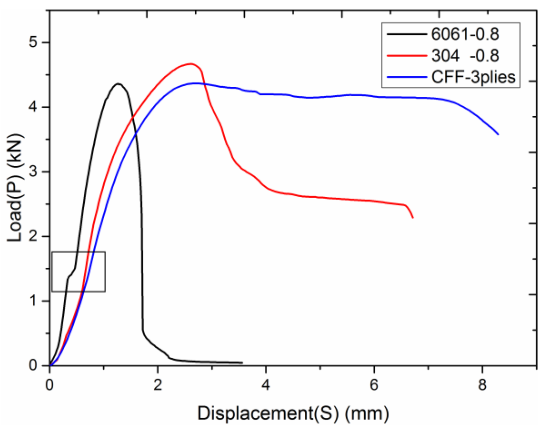
3. Result

Face-sheet thickness is an effect factor which has an influence on the mechanical properties and failure mechanism of aluminum foam sandwich structures (Mohan *et al*. 2005, Zhang *et al*. 2016, Yan and Song 2016). To gain the best matched face-sheet thickness for the selected foam core, AFS with 4 kinds of face-sheet thickness (0.6 mm, 0.8 mm, 1.0 mm, 1.2 mm) were tested for each face-sheet materials before this study. The thickness of carbon-fiber was adjusted by number of the carbon-fiber plies. Results of the previous work indicated when the aluminum foam core was sandwiched by 0.8 mm thickness face-sheet or 1.0 mm thickness face-sheet, the average peak value and energy absorption value tended to be stable. Therefore AFS with 0.8 mm thickness and 1.0 mm thickness face-sheet could be regarded as a suitable selection to analyze the effects of face-sheet materials without any other factors. Load-Displacement curves of the tested specimens showed in Figs. 2 and 3 were not the average results of all the specimens of each type, but the AFS specimens had almost the same peak load value and energy absorption ability to the average values. Only single curve can represent the progress of AFS under three-point bending accurately, the average one may change the shape of the curves and cannot reflect the deformation and mechanical properties of the structure originally.

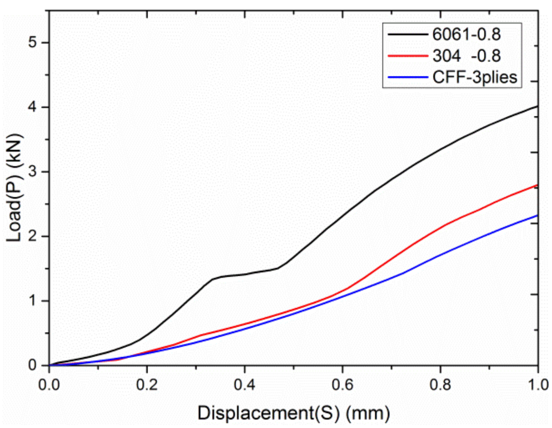
Fig. 2(a) showed the $P-\delta$ curves of AFS sandwiched by aluminum alloy 6061 and stainless steel 304 with face-sheet thickness of 0.8 mm and carbon-fiber fabric of 3 plies. Thickness of single carbon-fiber layer was 0.167 mm. When three layers were bonded together, the thickness was about 0.8 mm with adhesive. In the cases of AFS with stainless steel 304 and CFF face-sheets, the $P-\delta$ curves could be divided into three stages: linear-elastic stage, yielding plateau and failure stage. Firstly, the loads initially increased linearly with the extent of the indenter. The slopes

Table 3 Parameters the three-point bending test

Parameters	l	H	c	t	a	P
Values	80 mm	35 mm	15 mm	differed	10 mm	2 mm/min

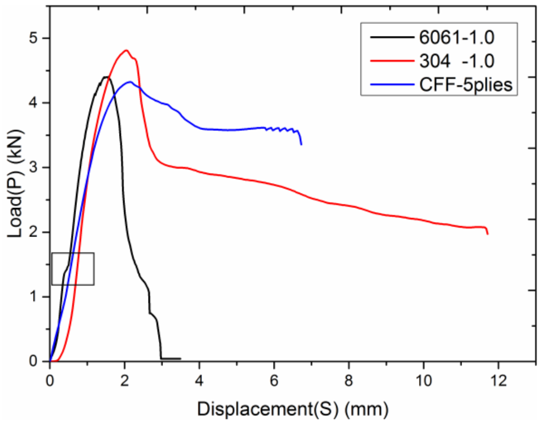


(a) The whole curves

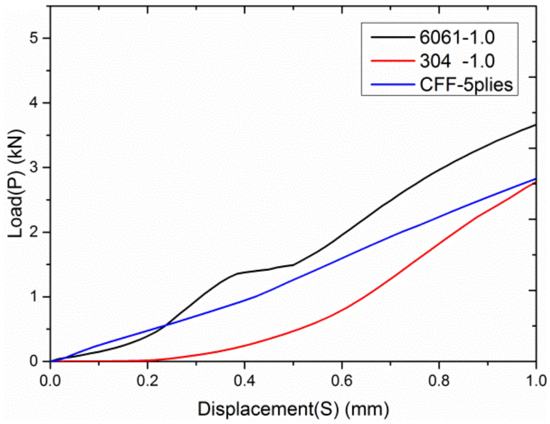


(b) Curve in the box of (a)

Fig. 2 $P-\delta$ curves of the AFS with face-sheet thickness of 0.8 mm (3 plies of carbon-fiber)

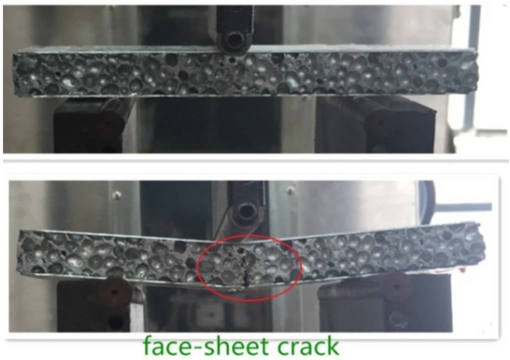


(a) The whole curves

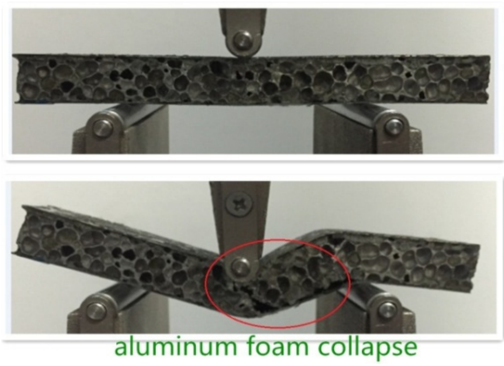


(b) Curve in the box of (a)

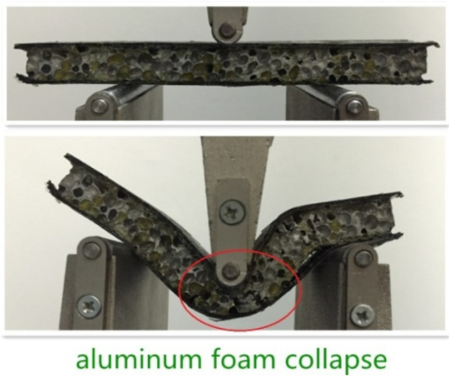
Fig. 3 $P-\delta$ curves of the AFS with face-sheet thickness of 0.1 mm (5 plies of carbon-fiber)



(a) AFS with aluminum alloy 6061



(b) AFS with stainless steel 304



(c) AFS with CFF

Fig. 4 Deformation of AFS with different face-sheet materials

of the curves can be representative of the structures' stiffness. Secondly, after reaching to a peak load, foam core collapse started and the curve went down slightly. With further loading, the face sheets bended and foam core collapsed as depicted in Figs. 4((b) and (c)). As known that there is a long yield stage, during which the stress is constant while the strain increases rapidly, for foam materials because of the structure trait (Zhang *et al*. 2016, Nammi *et al*. 2016). This feature had also extended to the AFS structures. There was a yield platform for AFS with stainless steel 304 and carbon fiber face-sheets clearly. Finally, the foam core collapsed completely and the yield platform ended. However, for 6061 face-sheet sandwiched AFS the yield platform did not appear. The AFS structure failed quickly after reaching its peak load and thus there was no collapse region. The initial linear stage of the three types of AFS was different too. From Fig. 2(b), the enlarged view of the rectangular box part in Fig. 2(a), there was evident platform in the $P-\delta$ curves of AFS with aluminum alloy 6061 face-sheet but no platform in the curves of aluminum alloy 6061 and stainless steel 304 sandwiched structures in the linear-elastic stage. When the thickness of the face-sheet panels increased from 0.8 mm to 1.0 mm, same results can get from Fig. 3. The peak load values of the three types of AFS were much of a size, but the energy absorption abilities were different completely.

Deformation and failure mode were of great important because they may determine the mechanical properties and application of the AFS. Fig. 4 shows the deformation of aluminum foam with different face-sheet materials. Deformations of the three types of AFS were different totally. In Fig. 4(a), aluminum foam sandwiched by aluminum alloy 6061, it can be seen that when the specimens was loaded, after a short displacement of indenter, the bottom face-sheet cracked and the foam core cracked followed by. There is no collapse of foam core almost. But in Fig. 4(b), no face-sheet crack happened until the foam core collapsed and cracked due to the transverse shear force. Similar result can gain from Fig. 4(c), AFS with 3 plies of CFF. The deformation modes were influenced by the face-sheet materials. The reason for this will be analyzed in the discussion part in detail.

4. Discussion

4.1 Effects of face-sheet materials on the flexural strength and energy absorption of AFS

It is clear that with the reinforcement of face-sheet panels, loading capacity of aluminum foam improved significantly. From our previous study, it found that the peak load value of the foam only beam under three-point bending was about 0.66 kN (Yan and Song 2016). But from Fig. 5(a), when aluminum foam was sandwiched by face-sheet with thickness of 0.8 mm or 1.0 mm, peak load value was around 4.5 kN, which was 6.8 times higher than foam only beams. Peak load value was determined by the combination of face-sheet and foam core, because there was the strength matching between foam core and face-sheet panels. If the foam core strength and face-sheet strength were selected properly, the sandwich structure may attain its maximum peak load value. When aluminum foam was sandwiched by aluminum alloy 6061 face-sheet, the face-sheet strength was not high enough to ensure the load can be transmitted to foam core, the whole structure cracked together. This was also the reason why there were no yield platforms of the $P-\delta$ curves of aluminum alloy 6061 face-sheet sandwiched AFS in Figs. 2(a) and 3(a). For this circumstance, aluminum foam did not come into effect. There is no clear foam core collapse and thus there is no platform in the curve. When foam core sandwiched by face-sheet with higher strength, such as stainless steel 304 and carbon fiber in this work, the sandwich structure had chance to subject to a transverse shear force and shear force was carried mainly by the core. Under this circumstance, foam core took its place as energy absorption material and collapsed as shown in Figs. 4((b) and (c)). During the collapse stage, energy was absorbed and the yield platform was appeared. This means that when face-sheet materials changed, the failure mechanism of the foam core differed. Only when the strength of face-sheet materials reached a certain value, foam core had chance to work effectively. From Fig. 2(b), the enlarged view of the rectangular box part in Fig. 2(a), there was evident platform in the $P-\delta$ curves of AFS with 6061 face-sheet but no platform in the curves of aluminum alloy 6061 and stainless steel 304 sandwiched structures in the linear-elastic stage. The reason for this was also the strength of the face-sheet materials. When the AFS was reinforced by aluminum alloy 6061 face-sheet, yielding of the bottom face-sheet appeared before foam core under relative lower load. But for AFS with stainless steel 304 and carbon fiber face-sheets, there were no face-sheet yield and also no core yield under lower load.

Energy absorption ability is the key property of AFS. It can be calculated by the area under the Load-Displacement curve. Fig. 5(b) shows the comparison energy absorption value of AFS with different face-sheets. In case of 6061 face-sheet AFS, energy absorption was 3.13 J and 4.29 J differed from face-sheet thickness. This was almost no energy absorption. The reason for this was low yield and tensile strength of face-sheet material lead to fracture of bottom face-sheet and the foam core has no chance to carry transverse shear force and collapse. But for stainless steel 304 and CFF face-sheet AFS, their energy absorption values were considerable. When aluminum foam was sandwiched by 1.0 mm stainless steel 304 face-sheet or 3 plies of CFF,

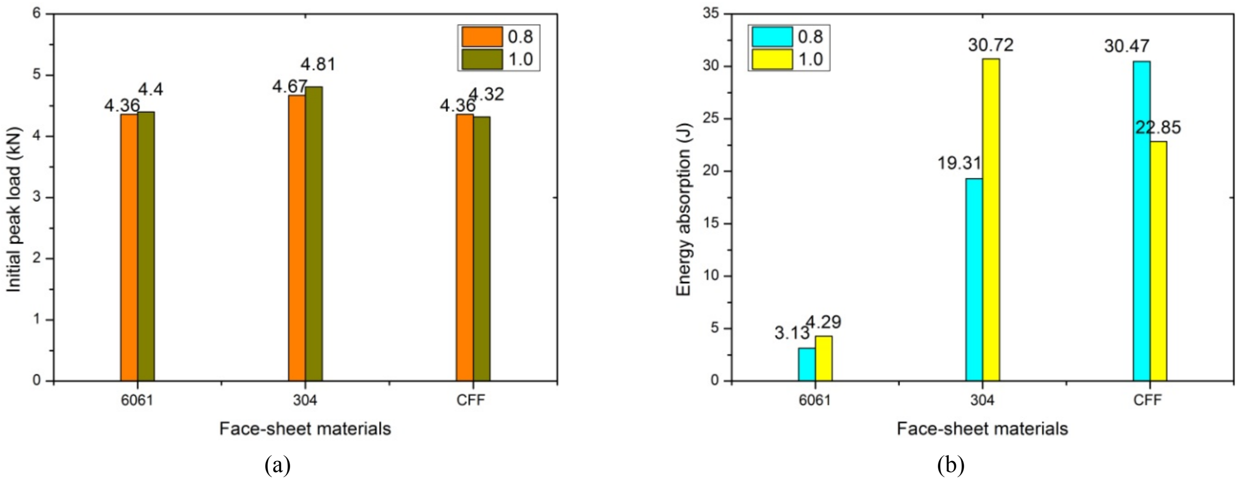


Fig. 5 Comparison of initial peak load and energy for face sheet materials: (a) initial peak load; (b) energy absorption

Table 4 Mass and increment mass of different specimens on average

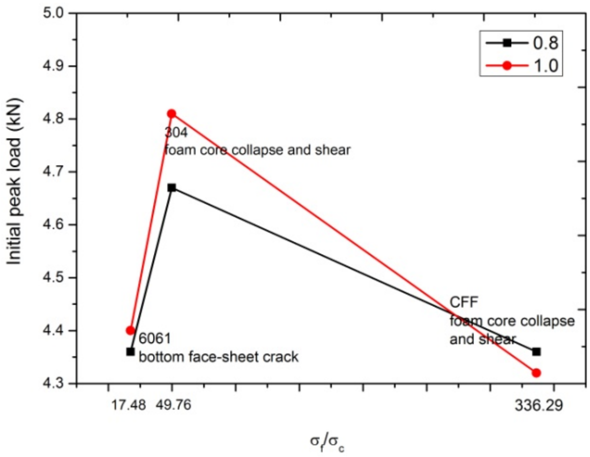
Face-sheet Thickness	6061		304		CFF	
--	Total mass (g)	Mass increment (g)	Total mass (g)	Mass increment (g)	Total mass (g)	Mass increment (g)
0.8 mm or 3 plies	67.31	19.62	100.71	53.02	66.55	18.86
1.0 mm or 5plies	73.82	26.13	120.58	72.89	75.16	27.47

the energy absorption capacity reaches to the maximum value (about 30 J).

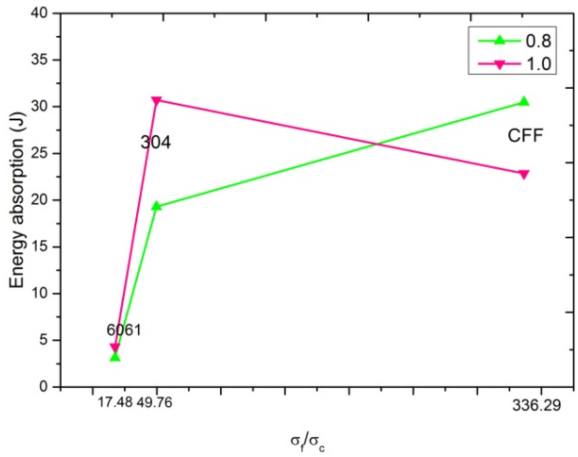
As it is known that lightweight is one of the most advantage of foam materials and it is also the reason why foam materials are so popular. But enhancement of sandwiching foam by traditional metal or non-metal face-sheets leads to the increase of weight and if the weight increased too much, it may lose the advantage of foam materials. Table 4 lists out the mass of each type of specimens and their increments compared to foam only specimens. When foam core is sandwiched by aluminum alloy 6061, the mass increment is 19.62 g when face-sheet thickness was 0.8 mm and 26.13 g when face-sheet thickness was 1.0 mm. The influence of weight was acceptable but the strength of aluminum alloy 6061 was too low and thus aluminum foam cannot come to play to absorb energy. When the face-sheet material changed to stainless steel 304, aluminum foam core took effect, its energy absorption was 5 times more than aluminum alloy 6061 sandwiched AFS. However, the mass increment doubled to the 6061 one. It was 535.02 g for 0.8 mm thickness specimens and 72.59 g for 1.0 mm thickness ones. This value was also double to the foam core itself and influenced the specific strength and stiffness seriously, even though the loading capacity and energy absorption ability of stainless steel 304 reinforced aluminum foam improved dramatically. Carbon fiber is a new light material with high strength. When the face-sheet changed to carbon fiber, the increase of weight was similar to aluminum alloy 6061 face-sheet but its flexural strength and energy absorption ability were as high as stainless steel 304 face-sheet AFS. Because of all these, CFF was considered to be the best choice among the three kinds of face-sheet materials for aluminum foam. When foam core was sandwiched by 3 or 5 plies of CFF, its loading capacity and energy absorption ability are good and stable and the increase of weight was similar to aluminum alloy 6061.

4.2 Effects of face-sheet materials on the failure mechanism of AFS

From Fig. 4, it was clear that the deformation and failure mechanism of the three types of AFS were different. When face-sheet was aluminum alloy 6061, the AFS failed by face-sheet yielding without collapse of the foam core. The sandwich structure deformed together. When face-sheets were stainless steel 304 and carbon fiber, the AFS failed by core shearing and collapse. This was corresponding to the result in (Wang *et al*. 2015). Failure mechanism of the AFS was related to the strength mis-matching of face-sheet panels and foam core. From Fig. 6(a), when versus strength ratio of face sheet to core was 17.48, there was no collapse of aluminum foam core but only crack of bottom face-sheet. Once the bottom face-sheet cracked, the whole structure failed completely. This also leaded to the low energy absorption as shown in Fig. 5(b). When versus strength ratio of face sheet to core increased to 49.76, the failure mechanism changed totally. The increase of σ_f / σ_c means the increase of face-sheet strength, once loaded, the force transmitted to foam core without crack at bottom face-sheet



(a)



(b)

Fig. 6 Comparison of initial peak and energy absorption versus strength ratio of face sheet to core: (a) initial peak load; (b) energy absorption and thus foam core collapsed and energy was consumed. In case of carbon fiber reinforced aluminum foam sandwich, failure mechanism was the same to stainless steel 304 ones, even though the σ_f / σ_c was much higher than stainless steel 304 ones. Which means there was a critical value of σ_f / σ_c. When the value exceeded the critical value, AFS failed by core shearing and collapse. When the value of σ_f / σ_c was less than the critical value, AFS failed by face-sheet crack. Fig. 6 reveals that energy absorption ability of aluminum foam sandwich was decided by the failure mechanism of the structure. If foam core can take its place and collapse during loading, energy can be consumed. The failure mechanism was determined by σ_f / σ_c. When σ_f / σ_c reaches to a certain value (49.76 in the present study), foam core can work efficiently. The famous collapse mechanism map for three-point bending indicates when face-sheet, core materials and the other geometry size were selected, the failure mechanism was decided by the ratio of foam core thickness to span of three-point test condition (Ashby *et al*. 2000). But in reality, geometry size of a certain component was determined already. Selection of material was of great important to determine the strength of face-sheet. σ_f / σ_c can be a standard value for design of AFS structure.

5. Conclusions

In the present work, three types of materials were selected as face-sheets to enhance aluminum foam core to study their influence on the mechanical properties and failure mechanism of aluminum foam sandwich. Several conclusions can be gained as follows:

- When aluminum foam was sandwiched by aluminum alloy 6061 face-sheets, face-sheet yield appeared under lower load and cracked at the peak load. Foam core cracked with the bottom face-sheet. No collapse occurred in the foam core. When the face-sheets changed to stainless steel 304 or carbon fiber, AFS failed by foam core shear and collapse. There were evident yield platform in the Load-Displacement curves of the AFS. Energy absorption ability of the 304 and carbon fiber reinforced aluminum foam sandwich was higher than that of the 6061 reinforced one. Peak loads of the three types of AFS were at the same size.
- For AFS had same strength and energy absorption ability, carbon fiber face-sheet AFS was the lightest. Its strength and energy absorption ability was similar to stainless steel 304 face-sheet AFS and its weight was similar to aluminum alloy 6061 face-sheet AFS.
- Aluminum alloy 6061 face-sheet reinforced sandwich structure failed by bottom face-sheet crack without foam core collapse and stainless steel 304 and carbon fiber fabric reinforced sandwich structures failed by bending and foam core collapse without face-sheet materials crack. Failure mechanism was related to the versus strength ratio of face sheet to core (σ_f / σ_c.). When this ratio reached to a certain value, foam core takes its place as energy absorbing material. More work is needed to gain the exact critical value of σ_f / σ_c, which is suggested to be a crucial value for design of aluminum foam sandwich structures.

In general, face-sheet materials affected the mechanical properties and failure mechanism of aluminum foam sandwich structure significantly. Choosing a proper face-sheet may determine the application of the structure. Further work is needed to find out the exactly critical value of σ_f / σ_c for the design of aluminum foam sandwich composite structure. Finite element simulation would be an efficient way to study the matching problem of AFS, in which different types of face plates can be concidered (Raianeesh *et al*. 2012).

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References

Aldoshan, A. and Khanna, S. (2017), "Effect of relative density on the dynamic compressive behavior of carbon nano-tube reinforced aluminum foam", *Mater. Sci. Eng. A*, **689**, 17-24.

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

Cheng, S.L., Zhao, X.Y., Xin, Y.J., Du, S.Y. and Li, H.J. (2015), "Quasi-static localized indentation tests on integrated sandwich panel of aluminum foam and epoxy resin", *Compos. Struct.*, **129**, 157-164.

Crupi, V., Epasto, G. and Guglielmino, E. (2013), "Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam", *Marine Struct.*, **30**, 74-96.

Gibson, L.J. and Ashby, M.F. (1997), *Cellular Solids: Structure and Properties*, (2nd Ed.), Cambridge University Press, Cambridge, UK.

Han, M.S. and Cho, J.U. (2014), "Impact damage behavior of sandwich composite with aluminum foam core", *Trans. Nonferrous Met. Soc. China*, **24**, 42-46.

Hao, Q.X., Qiu, S.W. and Hu, Y.B. (2015), "Development on preparation technology of aluminum foam sandwich panels", *Rare Metal Mater. Eng.*, **44**(3), 548-552.

Jing, L., Wang, Z. and Zhao, L. (2013), "Dynamic response of cylindrical sandwich shells with metallic foam cores under blast loading and Numerical simulations", *Compos. Struct.*, **99**, 213-223.

Kabir, K., Vodenitcharova, T. and Hoffman, M. (2014), "Response of aluminium foam-cored sandwich panels to bending load", *Composites: 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, C., Zhang, Y.X. and Ye, L. (2017), "High velocity impact responses of sandwich panels with metal fibre laminate skins and aluminium foam core", *Int. J. Impact Eng.*, **100**, 139-153.

Lu, G. and Yu, T.X. (2003), *Energy Absorption of Structures and Materials*, Woodhead Publishing Ltd., Cambridge, UK.

Mohan, K., Hon, Y.T., Idapalapati, S. and Seow, H.P. (2005), "Failure of sandwich beams consisting of alumina face sheet and aluminum foam core in bending", *Materials Science and Engineering A*, **409**(1-2), 292-301.

Mohan, K., Yip, T.H., Idapalapati, S. and Chen, Z. (2011), "Impact response of aluminum foam core sandwich structures", *Mater. Sci. Eng. A*, **529**, 94-101.

Nammi, S.K., Edwards, G. and Shirvani, H. (2016), "Effect of cell-size on the energy absorption features of closed-cell aluminium foams", *Acta Astronautica*, **128**, 243-250.

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.

Rajaneesh, A., Sridhar, I. and Rajendran, S. (2014), "Relative performance of metal and polymeric foam sandwich plates under low velocity impact", *Int. J. Impact Eng.*, **65**, 126-136.

Steeves, C.A. and Fleck, N.A. (2004), "Collapse mechanisms of sandwich beams with composite faces and a foam core, loaded in three-point bending. Part II: experimental investigation and numerical modelling", *Int. J. Mech. Sci.*, **46**, 585-608.

Styles, M., Compston, P. and Kalyanasundaram, S. (2017), "The effect of core thickness on the flexural behavior of aluminum foam sandwich structures", *Compos. Struct.*, **80**(4), 532-538.

Wang, Y., Ren, X., Hou, H., Zhang, Y. and Yan, W. (2015), "Processing and pore structure of aluminium foam sandwich", *Powder Technology*, **275**, 344-350.

Xu, A., Vodenitcharova, T., Kabir, K., Flores-Johnson, E.A. and Hoffman, M. (2014), "Finite element analysis of indentation of aluminum foam and sandwich panels with aluminum foam core", *Mater. Sci. Eng. A*, **599**,125-133.

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., Int. J.*, **21**(5), 1145-1156.

Zhang, B., Lin, Y., Li, S., Zhai, D. and Wu, G. (2016), "Quasi-static and high strain rates compressive behavior of aluminum matrix syntactic foams", *Compos. Part B*, **98**, 288-296.

Zu, G.Y., Lu, R.H., Li, X.B., Zhong, Z.Y., Han, M.B. and Yao, G.C. (2013), "Three-point bending behavior of aluminum foam sandwich with steel panel", *Trans. Nonferrous Met. Soc. China*, **23**(9), 2491-2495.

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