Flexural Behavior of Open-Cell Aluminum Foam Sandwich Under Three-Point Bending

Muataz H. F. Al Hazza, Nur Asmawiyah Bt. Ibrahim, Erry Y. T. Adesta, Nor A. Endut, Mohammad Yeakub Ali

Abstract--- ***Aluminum foam sandwich (AFS) panels are one of an advanced material that has various advantages such as lightweight, excellent stiffness to weight ratio and high-energy absorption. Due to their advantages, many researchers' shows an interest in aluminum foam material for expanding the use of foam structure. However, there is still a gap need to be filling in order to develop reliable data on mechanical behavior of AFS with different parameters and analysis method approach. There are two types of aluminum foam that is open-cell and closed-cell foam. Few researchers were focusing on open-cell aluminum foam. Moreover, open-cell metal foam had some advantages compared to closed-cell due to the cost and weight matters. Thus, this research is focusing on aluminum foam sandwich using open-cell aluminum foam core with grade 6101 attached to aluminum sheets skin tested under three point bending. The effect Skin to core ratio investigated on AFS specimens analyzed by constructing load-displacement curves and observing the failure modes of AFS. Design of experiment of three levels skin sheet thickness (0.2mm, 0.4mm, and 0.6mm) and two levels core thickness (3.2mm and 6.35mm). a full factorial of six runs were performed with three time repetition. The results show that when skin to core ratio increase, force that AFS panels can withstand also increase with increasing core thickness.***

Keywords: Aluminum Foam Sandwich; Open-Cell; Three-Point Bending; Flexural Behavior

1. INTRODUCTION

Demand for the use of porous material in industries nowadays is increasing by years. This is due to the need of decreasing the weight of structural parts. One of these materials are the foam materials. At the beginning of production of foam material, polymer-based foam had been introduced. However, polymer had limitation in heat resistant [1] besides, there is an increasing in the amount of waste as increasing the used of polymer foam in shipbuilding industries [2]. Thus, metal foam was developed and one of the famous metals foams with many industries applications is aluminum foam. One of the advantageous for metal foam is the easier to recycle compared to polymer foam [3]. Conventionally, the polymer foam is used as a core in variety application. However, polymer foam had many limitations such as low heat resistance. Thus, metal foam produced to overcome the problem. Metal foam have interesting properties as a sandwich's core likes good stiffness and strength to weight ratio, good sound damping, excellent energy absorption and thermal insulation [4]&[5].

Nevertheless, foam itself is weak therefore; the sandwich panel introduced to increase the strength of the foam core. Sandwich panel is made up from two stiff faces and separated by lightweight core [6] & [7]. By adding stiff face sheets to the core, the moment of inertia also increased and produced stable structure to resist buckling load and bending with minimum weight [6]. Metal foam consist of two types of cell topology which is open-cell and closed-cell foam.

Open-cell metal foam had many advantages compared to closed-cell such as high interconnectivity, high moisture absorption and chemical leached. Closed-cell metal foam had disadvantage in term of closed-cell may contain undesired chemical. Aluminium foam can be different based material such as aluminium 6061 which produces by [3]. They used powder metallurgical technology by using metal powder and foaming agent of TiH2. Yet aluminum foam itself is weak, thus aluminium foam sandwich (AFS) were produced which consist of foam as core and thin solid material as upper and lower skin [3].

There were many advantages of sandwich panels with metallic foam cores. Crupi and Montanini [5] stated that the properties of AFS were high energy dissipation, low specific weight, high damping, thermal insulation and high strength impact. According to [3], the porous materials had grown in various application because of its excellent physical properties. This also supported by [1] who reported that metal foam have high impact energy absorption, good strength and stiffness to weight, electromagnetic wave absorption, good sound damping, non-combustibility and thermal insulation.

AFS geometries and physical properties can be varied according to each purpose such as core thickness, foam density, cellular morphology and face thickness [5]. Sandwich panels can be fail with different failure or collapse mode depending on their geometries, physical and mechanical properties. Li et al. [8] mentioned that the possible failure modes of sandwich beams are core yielding and shear, face wrinkling and yielding and indentation. This supported also by Crupi and Montanini [5] which stated that failure mode for bending can be face wrinkling, face yielding, indentation and core shear. The used of sandwich panel with foam core are often used today to minimize the weight of structural parts which gradually will reduce consumption of oil and energy. Besides, the lightweight

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Muataz H. F. Al Hazza, Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (mmyali@iium.edu.my)

Nur Asmawiyah Bt. Ibrahim, Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (mmyali@iium.edu.my)

Erry Y. T. Adesta, Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (mmyali@iium.edu.my)

Nor A. Endut, Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (mmyali@iium.edu.my)

Mohammad Yeakub Ali, Department of Manufacturing and Materials Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (mmyali@iium.edu.my)

sandwich panels will reduce the cost of associated with handling the panels and transporting.

Aluminium foam sandwich now are commonly used in many structural parts in different industry. For instance, sandwich panels now used in vehicle component such as rotor blades of helicopters [3]. One of the factors can be considering is by lighter the weight of the vehicles and it can be solving by using aluminium foam. Another application of sandwich structure with aluminium foam core was crash box attached to bumper. Aluminium foam can absorb impact forces and can reduce the damage of car body at low speed [5].

However, Sandwich panels can be failing with different failure or collapse mode depending on their geometries, physical and mechanical properties. According to D'Urso and Maccarini [9], they identified five different bending modes which is regular, local instability, generalized pull out, off-line bending and face yield. Regular bending modes are where the panel bends up to 90o. While the local instability happened when the fold developed in non-symmetrical position and create local detachment between upward skin and core. Next is generalized pull out which means the large part of the tense cause separation of skin and core. Off-line bending happened when bending of the specimen form between half dies and punch and it is non symmetry pattern. Lastly, the bending mode form when loaded less than three point bending is face yield. Face yield is bending mode happened when the tensile fracture form along the bending line.

The failure modes and deformation of sandwich panels when loaded under three point bending found by [10] were large inelastic deformation and face wrinkling. Large inelastic deformation happened at maximum bending moment which causes the highest deflection on the mid span of specimen. Face wrinkling takes place when the face sheet used too thin with strong core. There is waviness of skin. Besides that, writers also found that there was present of core shear in all specimens with interfacial failure. This is because of adhesive layer used had lower strength compared to core strength. For quasi-static punching test, they discover another types of failure modes which is core shear failure at boundary and centre area, upper skin wrinkle, bottom skin fracture and lastly interfacial failure.

Kabir et al., [11] reported that there were four types of failure deformation found in three point bending test of AFS. Core shear failure happened when the thin core attached with skins that were thick and high strength. Core shear also happened when the sandwich panels consist of thick and low yield strength of skins. Second failure deformation found was indentation failure. It is found when the sandwich panels fabricated using thin high strength face sheets and thick cores. Usually the thickness of core is greater than 30 mm and face sheet thickness thinner than 0.79 mm. The failure mode of core shears change to indentation when the support span was changing form 80 mm to 40 mm. The third failure deformation was facing yielding. This type of failure happened when thin cores attached with thin low strength skins which is the thickness is 10 mm and 0.4 mm respectively. Besides, by changing the thickness of core will also change the types of failure which is indentation to face yielding. Lastly, Kabir et. al. [11] also mentioned in a sandwich panel can happen two types of failure. For example, when the when span length higher than 90 mm the core shear and indentation will happen. While, when span length less than 80 mm, core shear and yielding will happen.

Metal foam consist of two types of cell topology which is open-cell and closed-cell foam. Different researchers have investigated the mechanical behavior of sandwich panels with aluminium foam core under three point bending. However, most of the researchers focusing on closed-cell aluminium foam core. Least of them were investigated the flexural behavior of sandwich panel with open-cell foam core. Therefore, this present study examines the flexural behavior of aluminium foam sandwich (AFS) with open-cell foam core loaded under three point bending. The failure modes and load-displacement curves of the aluminium foam sandwich is compiled and analyzed.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and fabrication

Open-cell aluminium foam was used as a core of sandwich structure in this research with density 0.2 g/cm3. The base material of aluminium foam was aluminium 6101. Two levels of core thickness of 3.2 mm and 6.35 mm used with three levels of skin thickness (aluminium 6061-0) of 0.2 mm, 0.4 mm and 0.6 mm. Both core and skin sheet was attached using Araldite epoxy resin and hardener. The sandwich left for 48 hours to complete cure. Some weight or load placed on top of the specimen to make sure binder separated evenly. In order to conduct three point bending test on aluminium foam sandwich, rectangular specimens used according to ASTM C393 with width and length 20 mm and 150 mm respectively. Figure 1 below shows rectangular specimens of AFS ready to be test under three point bending.

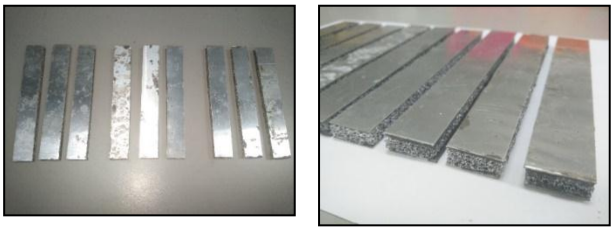


Fig.1: AFS specimens for three point bending test.

2.2 Experimental methods

Three point bending test was conducted by means of a universal INSTRON machine using 100 KN load with constant speed rate of 6 mm/min. Bending tests were carried out by controlling the input variables of core and skin thickness combination. Design of experiment of three levels skin sheet thickness and two levels core thickness were developed using full factorial in JMP statistical analysis. Six numbers of runs with different input variables combination were performed with three times repetition to ensure the accuracy. Table 1 below shows design of experiment for input variables.

Table 1: Design of experiment for three point bending test

No. of run	Skin thickness (mm)	Core thickness (mm)
1	0.2	3.2
2	0.4	3.2
3	0.6	3.2
4	0.2	6.35
5	0.4	6.35
6	0.6	6.35

3. RESULTS AND DISCUSSION

Effect of skin to core ratio (t/c) on mechanical behavior of open-cell aluminium foam sandwich also observed under three point bending test. Six run of experiment conducted with different input parameters combination with repetition of three times. Design of experiment for three levels of skin thickness, t that is 0.2 mm, 0.4 mm and 0.6 mm and two levels of core thickness, c that is 3.2 mm and 6.35 mm constructed using full factorial in JMP statistical analysis software. Experiments conducted under constant velocity, which is 6 mm/min according to ASTM standard of C393. The output responses were bending force, P and displacement, d. The constant support span, s length used was 100 mm. The diameter of roller puncher and supports were 13 mm. Table below shows the input parameters combination and output responses of AFS behavior repeated three times which is T1, T2 and T3. Analysis continued by calculating average of the outputs value and tabulated in the tables below. Table 2 shows the bending force of AFS for all repeated specimens and their average value. Table 3 shows the bending displacement, d of AFS.

Table 2: Bending force compilation of AFS

Run	Input parameters			Output parameter (Bending force, N) 150 mm x 20 mm			Average
	t (mm)	c (mm)	t/c	T1	T2	T3	
1	0.2	3.20	0.06	155.37	143.48	148.27	149.04
2	0.4	3.20	0.13	221.65	184.40	169.13	191.73
3	0.6	3.20	0.19	275.89	274.05	367.54	274.97
4	0.2	6.35	0.03	204.02	210.57	229.94	214.84
5	0.4	6.35	0.06	285.60	323.65	244.42	284.56
6	0.6	6.35	0.09	351.69	375.73	356.34	361.25

Table 3: Bending displacement data compilation of AFS

Run	Input parameters			Output parameter (Displacement, mm) 150 mm x 20 mm			Average
	t (mm)	c (mm)	t/c	T1	T2	T3	
1	0.2	3.20	0.06	9.03	6.16	8.04	7.743
2	0.4	3.20	0.13	19.09	19.79	8.86	8.86
3	0.6	3.20	0.19	11.31	14.56	14.07	14.32
4	0.2	6.35	0.03	22.35	25.39	27.62	25.12
5	0.4	6.35	0.06	37.19	32.43	36.06	35.23
6	0.6	6.35	0.09	37.72	21.64	36.37	37.05

In order to have better understanding on the pattern of the flexural behavior of AFS cause by skin to core ratio, force-displacement curves of all specimens were constructed using line graph. Figure 2 below shows the force-displacement curve of AFS when loaded under three point bending test.

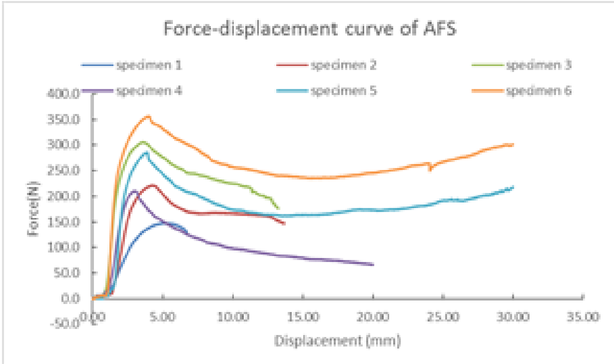
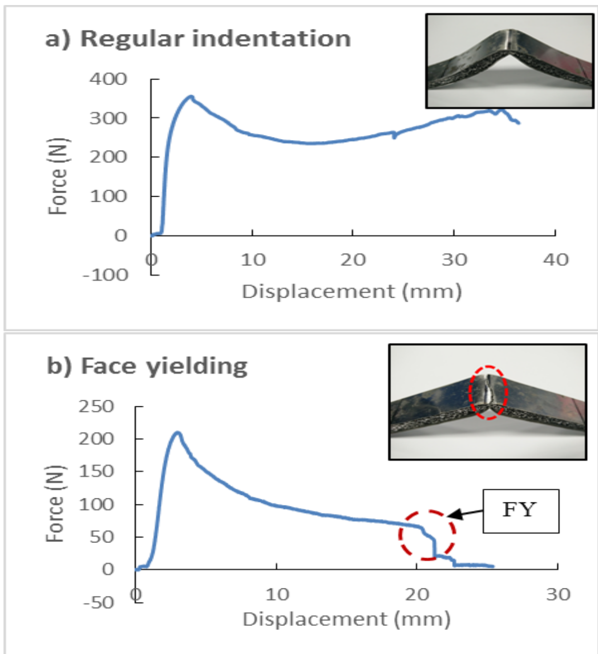


Fig.2: Force-displacement curve for three point bending test

The graph shows a linear deformation for all specimens which it displays a permanent deformation after plastic yielding begins. However for AFS with thinnest face sheet tend to occur face yielding which the face cracked after AFS reached maximum stress or force. This may cause of tensile failure of the lower face sheet of AFS [6]. Based on table and graph shown above, it can be summarize that when skin to core ratio increase, force that AFS panels can withstand also increase with increasing core thickness.

Besides that, analysis of AFS when loaded under three point bending also conducted by observing the failure modes of AFS specimens. Failure modes of AFS observed in the three point bending experiments and shows in the Figure 4 below with the force-displacement curve. Failure modes observed were regular indentation (R), face yielding (FY), core shear (CS), offline bending (OB) and interface failure (IF).



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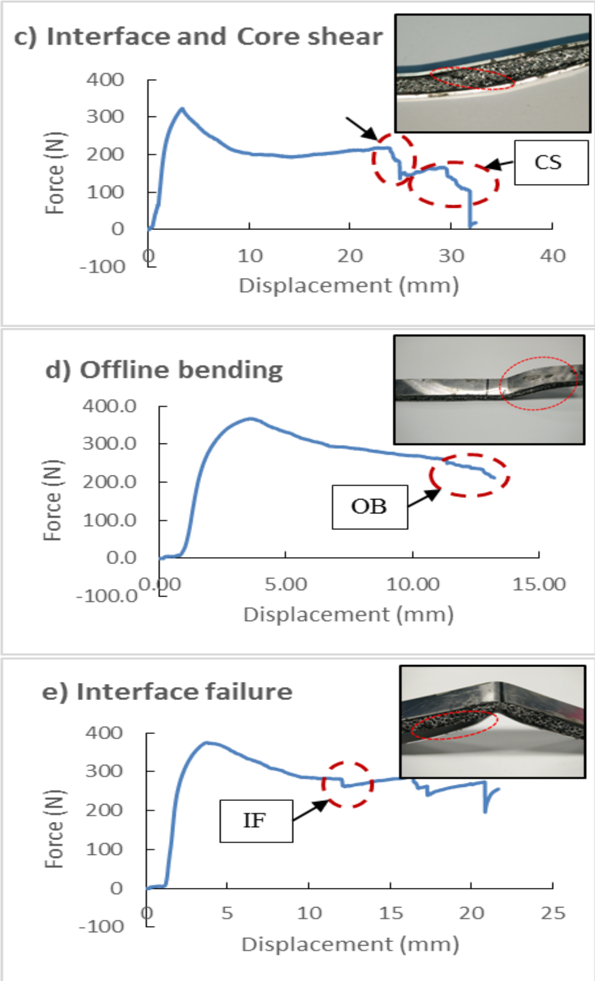

Fig.3: Failure modes of AFS when loaded under three point bending

Based on observation, it found that, when the skin sheet used is too thin which is 0.2 mm and below, it will cause face yielding and will reduce the maximum bending stress and force for both core thicknesses. Cracking progress at the lower skin under the roller puncher was due to tensile failure at the lower face sheet [12]. Other than that, when the skin sheet is too thick such 0.6 mm, it will lead to possible of interface failure to happen. Regular or symmetry deformation of AFS of core thickness 6.35 mm found and it is in line with finding of Kabir et al [11]. Besides, it found that thicker skins would cause shear crack as dominant failure for open-cell foam. Styles et al., [4] also found thicker skins appear to increase shear stress in closed-cell foam, which will cause shear crack as major failure mechanism [4]. However, for open-cell AFS, it is found that, core shear tend to occur after interface failure occur as in Figure 3c compared to closed cell the core shear occur by itself.

4. CONCLUSION

In summary, it can be concluded that, the three point bending test successfully conducted. The load-displacement curves show that increasing the skin to core ratio will increase force that AFS panels can withstand. While failure modes of AFS when loaded under three point bending indicated that when the skin was too thin, it would cause face yielding to appear. However, when the skin is too thick, it will lead to interface failure to happen. Thus, in order to have stable sandwich structure, appropriate choice of core and skin thickness need to be observed according to ASTM standard of stable ratio.

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