Applied Innovative Research
Vol. 1, September-December 2019, pp. 194-199

Assessing factors affecting the flexural behavior of metallic foam in-filled sandwich panel

Anshul Badkul & Sanjeev Saxena*
CSIR- Advanced Materials and Processes Research Institute (AMPRI), Bhopal 462 026, India

Received 12 November 2019; Accepted 05 December 2019

The performances of metallic foam are required to improve under flexural loading condition to fulfill the industrial need. In the present work existing literature has been evaluated to understand the factors (foam density, span length, aspect ratio of test specimen, foam core and face sheet thickness) affecting flexural property of foam in-filled sandwich panel. Delamination of foam in-filled sandwich panel has been reported as the major failure mode during the flexural test. It has also been reported that the metallic bonding between metallic foam and face sheet avoid the chance of delamination under flexural loading conditions. There is also a need to have standard test procedure and standard test geometry to evaluate flexural property of metallic foam in-filled sandwich panel. Its evaluation using FEM based techniques are also reported in brief.

Keywords: Metal foam, Sandwich panel, Finite element analysis, Three point bending, Failure mechanism

1 Introduction

Aluminum foams are known for its light weight, higher specific strength and excellent energy absorption characteristic under compressive loading conditions[1-4]. To fulfill the industrial requirement of using metallic foam as structural member bare aluminum foam has weak flexural property. To utilize the foam to its maximum potential there is a requirement to evaluate study and improve its flexural behavior. Metallic foam in-filled sandwich panel is expected to perform better under flexural loading condition[5]. The load transfer in sandwich panel is understood through bending of two sheets and due to shearing of core. Sandwich metallic foam in-filled material belongs to the group of anisotropic materials, where its strength properties changes with applied load. Therefore, metallic foam covered with two thin metal sheets constituting foam in-filled sandwich panel can be used in many industrial applications (automotive, defense etc)[6-10].

Several researchers have worked on the evaluation of flexural property of foam filled sandwich panel using three point bend test[11-14]. Many researchers have discussed on the bonding between the metal sheet and foam core[15-17]. Some of researchers construct finite element model to simulate the flexural strength of foam in-filled sandwich panel[18-19]. To achieve extensive industrial use of foam in-filled sandwich panel a review of work is required to carry out to understand how to evaluate its flexural properties and what are the parameter affecting its.

In the present investigation review of work carried out by researchers to synthesize foam in-filled sandwich panel and to evaluate its deformation behavior has been done. Three stage deformation behaviors are reported to observe during the flexural test of sandwich panel. It has initial elastic deformation followed by face sheet failure and then comes the aluminum foam core failure stage. The flexural behavior of foam in filled sandwich panel depends on metallic alloy used, synthesis route, the type of bonding agent between metal face plate and foam core, thickness of sandwich panel, span length and etc. Therefore the review work carried out in this present effort has been categorized under various sections. These are focusing on the methods used in the synthesis of foam, fabrication of foam in-filled sandwich panel, the effect of dimensions of experimentally tested specimens and also the numerical work carried out to evaluate behavior of sandwich panel.

2 Synthesis of Foam

Using liquid and powder metallurgy route several attempted have been made to synthesis foam to be used in sandwich panel. Both polymer foam and metallic foam had been used as core in-filled in sandwich panel. In most of the cases aluminum foam

*Corresponding author: (E- mail: san_bpl@yahoo.com)

is used as core in metallic foam in-filled sandwich panel. Several materials and manufacturing methods were used for making aluminum foam. Y. K. An *et al.*[20] used pure aluminum matrix material for making foam using calcium and magnesium as a thickening agents and titanium hydride (TiH_2) as a foaming agents, whereas Long Wan *et al.*[21] used calcium and titanium as a thickening agents and titanium hydride (TiH_2) as a foaming agent. Similarly using liquid metallurgy route, Zhibin Li *et al.*[22] also used titanium hydride (TiH_2) as a foaming agent. In metallic foam synthesis to be used for sandwich panel, M. Malekjafarian *et al.*[23] used aluminum alloy (A356) matrix material and silicon carbide (SiC) as a thickening agent and calcium carbonate ($CaCo_3$) as a forming agent. Chang Yan *et al.*[11] used aluminum alloy (Al7050) matrix material and carbon fiber as a thickening agent. The information about the foaming agent has not been reported in this literature. Using powder metallurgy route, Guo-yin ZU *et al.*[15] used AlSi9Mg alloy powder as a matrix material and titanium hydride (TiH_2) powder as a foaming agent. Similarly, Isabel Duarte *et al.*[24] used aluminum alloy (AlSi7). Most of the researchers[17,25] used aluminum matrix through liquid metallurgy route but in some cases the information of thickening agent and foaming agent had not been reported. In the synthesis of metallic foam titanium hydride (TiH_2) is mostly used as a foaming agent.

3 Synthesis of Foam In-filled Sandwich Panel

Foam in-filled Sandwich panel constitutes of a thick aluminum foam core covered with two thin metal face sheets. To fabricate the foam in-filled sandwich panel different types of binding agents were used in-between metal foam and metal sheet. Guo-yin ZU *et al.*[25] reported that the face sheets and foam core were bonded together by the polyamide-epoxy resin with equal mass ratio, and kept at ambient temperature for a day. Isabel Duarte *et al.*[24] fabricate the sandwich panels with aluminum foam core bonded with two face-sheets using a thin layer of Araldite. Ning-zhen Wang *et al.*[17] fabricated the sandwich panels with two kinds of commercial adhesives i.e. green−red glue and epoxy resin. In this it is reported that the highest flexural strength of the metallic foam in-filled sandwich panel is achieved using epoxy resin binder as compared with green-red glue.

Some of the researchers[10,15,21] also reported work on the development of metallic bonding between face sheet and foam core. Guoyin Zu *et al.*[15] found that the flexural strength of metallic foam sandwich panel with metallic bonding is stronger than the adhesive bonding with no delamination found in between face sheet and foam core. In addition it is reported that the metallic bonding interface between face sheet and foam core improves the structure stiff and energy absorbing capability. Long Wan *et al.*[21] reported that the metallic foam sandwich panel with metallic bonding between face sheet and Al foam core has been produced by the method of fluxless soldering with surface abrasion assist by vibrations. The excellent metallic bonding and no delamination has been found in-between face sheet and foam core as reported[21,26].

4 Failure Mechanism of Foam In-filled Sandwich Panel

As can been seen in Fig. 1 most of the researchers[21,22,25,27,28] have observed the deformation of foam in-filled sandwich panel occurring in three stages: (I) linear elastic deformation stage, (II) dense skin failure (III) foam core failure stage. During stage I, both face sheet and foam core undergoes elastic deformation. The linear stage I, reaches at its end when the load reaches almost to its peak value. In stage II due to the initiation of crack on the tensile side of face plate the load decreases initially then it remains constant (Fig. 1). During this stage the plastic deformation took place and it remains for a longer displacement. Once the skin is fractured during stage II, the load is transferred to the core and the cracks rapidly propagate to the compressive side. During the stage III, whole sandwich panel failed completely due to core shear failure or debonding of the metal sheet from foam core. In sandwich panel Y. K. An *et al.*[20] found failure regions only at the centre of flexural test samples where no delamination is detected. Cracks finally grow from inclusion regions, and brittle fracture as the main fracture mechanism was reported.

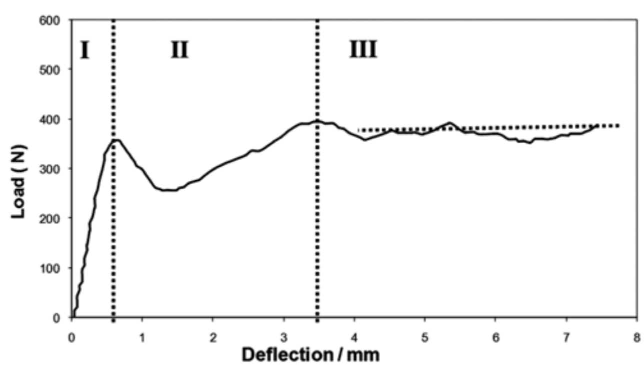

Fig. 1 — Three stage deformation behavior of sandwich panel.

5 Flexural Strength Evaluation of Sandwich Panel

The flexural test provides the data for the modulus of elasticity in bending, the load – displacement curve, peak load value (flexural stress), absorbed energy (flexural strain). Utilizing the experimental load - displacement curves many researchers[27,29,30] evaluate the flexural behavior of sandwich panel in terms of flexural strength (σ), flexural strain (ε_f) and modulus of elasticity (E_b) as follows:

$$\sigma = \frac{3Fl}{2bd^2} \quad \dots (1)$$

$$\varepsilon_f = \frac{6Dd}{l^2} \quad \dots (2)$$

$$E_b = \frac{l^3 m}{4bd^3} \quad \dots (3)$$

Where, F, d, b, and l refer to load, specimen width, specimen thickness and span length in millimeters, respectively. The m and D refers to the slope of tangent to the initial straight line portion of the load-displacement curve and the maximum deflection at the centre of the beam (mm). in terms of above parameters many researchers evaluated the flexural behavior of sandwich panel and try to understand the effect of foam density, span length, thickness and aspect ratio of test specimen.

5.1 Effect of foam density

Researchers[31,32] have also reported that the bending strength increases and deformation decreased with the increase in foam density. The physical properties of sandwich panel are also reported to affect by the density variation of foam. With the increase in foam density, there is an improvement in wall thickness of foam resulting in enhancement in stiffness and strength of the foam in-filled panel[23,33]. The mechanical properties such as flexural modulus, flexural strength and energy absorption capacity values increases with increases in foam density. It is also reported that the magnitude of density achieved in foam is strongly dependent on the manufacturing route and various synthesing parameters. A power law relationship to its density possesses the strength of metal foam. It signifies that 20% dense material is more than twice as strong as a 10% dense material[11,34].

5.2 Effect of span length

The flexural properties of sandwich panel are affected by varying the span length due to its inverse relationship with force. Similar observations were reported by Emre Kara *et al.*[12] in the experiment of foam in-filled sandwich panel subjected to three point loading. It has been showed by Xiaolei Zhu *et al.*[18] that in foam in-filled sandwich panel there is a reduction in critical load with the increases of span length. It was reported that the span length controls the shape of the failure mode, being symmetric for larger spans and asymmetric for smaller spans. In longer spans, only core yielding failure is reportedly observed in the top skin around the loading roller. Failure in sandwich panel of shorter span occurs due to shearing in the core and in the top skin on the side of the roller[16,26].

5.3 Effect of thickness of foam core or face sheet

Guo-yin ZU *et al.*[25] reported that the bending load increases with the increase of thicknesses of both steel panel and foam core. The flexural strength of foam in-filled sandwich panel is affected by thickness of face sheet because the face sheet provides a significant strength for the whole sandwich panel. Emre Kara *et al.*[12] reported that in sandwich panel, the S-Glass Woven fabrics used as a covering plate and increase in thickness of foam core improve the load carrying and energy absorption capacity. It was also reported that load carrying capacity and energy absorption ability of sandwich panel is affected by thickness of core foam[12,17] and face sheet[17]. When changing the upper face sheet from Al to galvanized steel of same thickness, the specific bending flexural strength is increases by 23.83% [35].

5.4 Aspect ratio of test specimen

While evaluating the flexural behavior of foam in-filled sandwich panel, various sizes of the test specimens had been used. Table 1 show that the variation of size of flexural test specimens used by various researchers for evaluating the flexural behavior of foam in- filled sandwich panel. It is observed that the depth and width of the test specimen varies from 10 to 50 mm. There is also a large variation of span length varying from 40 to 250 mm used in flexural test. It comes out, that there is a huge variation in ratio of cross section dimensions aspect ratio, i.e., (width to depth ratio) of test specimens varying from 0.6 to 8.0. There is also a huge variation in ratio of span length to width and span length depth of the specimen varies from 1.87 to 8.33 and 2.29 to 18, respectively. It comes out that there is a need to study the effect of test specimen size and also to

Table 1 — Details of test specimens used in flexural strength evaluation

Name of Authors (Year)	Depth (D, mm)	Width (W, mm)	Span Length (L, mm)	Ratio		
				Width to Depth (W/D)	Span to Depth (L/D)	Span to Width (L/W)
Y.K. An et. al. (2017)	19	40	120	2.11	6.31	3
Chang Yan et. al (2017)	15	30	80	2.00	5.33	2.66
Ning-zhen Wang et.al. (2016)	10	50	180	5.00	18	3.6
Emre Kara et. al. (2015)	14, 19	50	150	3.57, 2.63	10.71, 7.89	3
Momd Yaseer Omar et. al (2015)	11	15	80	1.36	7.27	5.33
L. Wan et al. (2015)	17.4	15	40	0.86	2.29	2.66
Zhibin Li et. al. (2014)	10, 20, 30, 40, 50	30	250	3, 1.50, 1, 0.75, 0.60	25, 12.5, 8.33, 6.25, 5	8.33
Tudor Voiconi et. al. (2014)	25	25	100	1	4	4
Guo-yin ZU et. al. (2013)	10, 20, 30, 40, 50	80	150	8, 4, 2.67, 2, 1.6	15, 7.5, 5, 3.75, 3	1.87
Guo-yin ZU et. al. (2012)	11.5	10	50	0.87	4.34	5
Liviu Marsavina et. al. (2010)	12	12	90	1.00	7.5	7.5
Isabel Duarte et. al (2010)	15	33	96	2.20	6.4	2.90
Jilin Yu et. al. (2008)	10, 20, 30, 40, 50	30	200	3, 1.50, 1, 0.75, 0.60	20, 10, 6.66, 5, 4	6.66
Xiaolei Zhu et. al. (2014)	10	44.5	167	4.45	16.7	3.75
Fa Zhang et. al (2013)	12	30	100	2.50	8.33	3.33

standardize the test specimen used in evaluating the flexural behavior of foam in filled sandwich panel.

6 FEM Based Evaluation

Using simulation technique not many researchers had worked on evaluating behavior of sandwich panel. The Nada S. Korim *et al.*[30] modeled mechanical behavior of foam in-filled sandwich panel using isotropic elasticity and isotropic crushable foam hardening plasticity. The elastic properties are completely defined by giving the Young's modulus, and the Poisson's ratio. In FEM analysis of Titanium foam crushable model is used to describe its compressive and bending behavior with having different porosity. The numerical results for compression tests were reported to be in good agreement with the experimental results whereas; the bending results were reported to deviate at higher displacement. Experimental results of load-displacement curve were used to validate the simulation results obtained by Fa Zhang *et al.*[19] from the model of sandwich panel created using finite element analysis. It was reported that the load carried by the sandwich structure initially increases linearly while the core and skins were being stressed. The experimental and numerical investigation results reported for the sandwich structure showed sudden brittle type failure due to shear failure of the core and compressive failure of the skins followed by debonding between the skin and the core. Using three point bending FEM model, Xiaolei Zhu. *et al.*[18] predicted the collapse model of aluminum foam sandwich tested under three point bending. It was reported that FEM model illustrates well the damage initiations and linear damage evolution law can describe well the sandwich collapse mode of core shear. It was also numerically found and reported that the critical load decreased by increasing the span.

7 Discussions

Several materials and manufacturing routes have been used for the synthesis of foam. In the synthesis of metallic foam in-filled sandwich panel titanium hydride is mostly used foaming agent and liquid route as a manufacturing route. Various types of thickening agent such as calcium, magnesium, titanium, silicon carbide (SiC) particles etc have been used in the synthesis of foam. Various types of binding agents such as epoxy resin, green – red glue, polyamide resin, araldite etc. were used in between the face sheet and metal foam core to fabricate the foam in filled sandwich panel. The flexural strength of metallic bonding between the face sheet and metal foam core is reported to be stronger than the adhesive bonding. The failure mode of foam in-filled sandwich panel can be expressed as the initial crush and shear damage of foam core, and delamination of glued interface at large bending loads. The mechanical properties of foam in-filled sandwich panel is also affected by the varying the density of foam, span length, thickness and aspect ratio of test specimen cross section. The flexural strength of sandwich panel is also affected by replacing the Aluminum face sheet to galvanized steel face sheet of same thickness. There are variations of test span in flexural testing of sandwich panel reported in literature. There is also a significant variation in test specimen cross section used in flexural tests of sandwich panel. There is a need to carry out a study comparing the results containing different test spans and cross section of sandwich panel test specimen to standardize the procedure which will help in finalizing the represented test specimen geometry of sandwich panel to be used in evaluating its flexural property. It was also observed from the literature survey, there is also a need to carry out study on understanding the effect of using different types of binders and optimize its quantity while fabricating sandwich panel. It is also noted that there is a requirement to carry out a systematic approach for the evaluation of mechanical behavior of foam in-filled sandwich panel. The effect of test specimen size on the flexural behavior of the sandwich panel has not studied and reported. The understanding of foam in-filled sandwich panel behavior under various loading conditions has also not been reported sufficiently. Its evaluation using FEM based techniques are also reported in brief.

8 Conclusions

In the present efforts a review of work carried out on synthesis of foam, fabrication of sandwich panel, its flexural behavior evaluation failure mechanism and factors affecting its performance have been studied. In direction of research its limitation and further scope of work needs to be carry out to exploit the commercial utilization of sandwich panel had been highlighted in the present paper. The conclusions and point that had come up from the present study on evaluating flexural behavior of sandwich panel are as following:

i. Generally aluminum foams are used in sandwich panel with calcium, magnesium, titanium and silicon carbide used as a thickening agent and titanium hydride used as a foaming agent.
ii. In fabrication of sandwich panel epoxy resin, green-red glue, polyamide resin and araldite are used as binders. Metallic bonding between metallic foam and metallic sheet reported to perform better as compared to other adhesive bonding.
iii. Failure of sandwich panel can be due to delamination or due to shear failure of core foam depending on the type of bonding used between the metallic foam core and metallic face sheet.
iv. Flexural strength of sandwich panel increases with increase in foam density and reduction in span length.
v. Flexural property of sandwich panel also depends on the thickness of metallic foam core and metallic face sheet and also on aspect ratio of cross section of test specimen.
vi. There is a need to standardize test procedure and specimen to evaluate flexural property of sandwich panel.
vii. There is also a requirement to put more systematic effort to numerical evaluation and understand the deformation behavior of sandwich panel to design it properly to meet the industrial requirements.

References

1 Banhart J, *Prog Mater Sci,* 46 (2001) 559.
2 Benedyk C J, *Mater Des Manuf Light Weight Vehicles*, (2010) 79.
3 Fernández L, & Wittig H, *International Trocellen Group Syposium, Madrid*, (4 May-6 May 2003) 1.
4 Fuganti A, Lorenzi L, Hanssen A G, & Langseth M, *Adv Eng Mater*, 2 (2000) 200.
5 Mohan K, Tick-Hon Y, Idapalapati S, & Seow H P, *J Mater Sci*, 42 (2007) 3714.
6 Huang L, Wang H, & Yang D H, *Intermetallics*, 28 (2012) 71.
7 Banhart J, & Seeliger H W, *J Adv Eng Mater,* 10 (2008) 793.
8 Salvo L, Belestin P, Maire E, Jacquesson M, Vecchionacci C, Boller E, Bornert M & Doumalin P, *J Adv Eng Mater*, 6 (2004) 411.
9 Hongjie L, Hao L, Zhihui Z, Yihan L & Guangchun Y, *Procedia Mater Sci*, 4 (2014) 39.
10 Hao L, Hongjie L, Wenzhan H, Xiao Z, & Guangchun Y, *J Mater Process Technol*, 230 (2016) 35.
11 Yan C, Xuding S, Hui Z, Chuanhe J & Shuo F, *J Compos Mater,* 52 (2018) 1887.
12 Kara E, Geylan A F, Kadir K, Karakuzu S, Demir M, & Aykul H, *Int J Civ Environ Eng,* 9 (2015) 596.
13 Mohan K, Hon Y T, & Idapalapati S, *Mater Sci Eng A,* 409 (2005) 292.
14 Crupi V, Epasto G, & Guglielmino E, *Metals,* 1 (2011) 98.
15 Guoyin Z, Binna S, Zhaoyang Z, Xiaobing L, Yongliang M, & Guangchun Y, *J Alloys Compd,* 540 (2012) 275.
16 Kabir K R, Vodenitcharova T, & Hoffman M, Int *J Mod Phys,* 23 (2009) 1733.
17 Wang N, Chen X, Li A, Li Y, Zhang H & Liu Y, *Trans Nonferrous Met Soc China*, 26 (2016) 359.
18 Zhu X, Ai S, Lu X, Cheng K, Ling X, Zhu L & Liu B, *Comput Mater Sci,* 85 (2014) 38.

19 Zhang F, Mohmmed R, Sun B & Gu B, *Appl Compos Mater,* 20 (2013) 1231.
20 An Y K, Yang S Y, Zhao E T & Zhou H A, *Mater Sci Technol,* 33 (2017) 421.
21 Wan L, Huang Y, Lv S & Feng J, *Compos Struct,* 123 (2015) 366.
22 Li Z, Zheng Z, Yu J, Qian C & Lu F, *Compos Struct,* 111 (2014) 285.
23 Malekjafarian M & Sadrnezhaad S K, *Mater Des,* 42 (2012) 8.
24 Duarte I, Teixeira-Dias F, Grac A, & Ferreira A J M, *Mechn Adv Mater Struct*, 17 (2010) 335.
25 Zu G, Lu R, Li X, Zhong Z, Xing-Jiang M, Han M, & Yao G, *Trans Nonferrous Met Soc China,* 23 (2013) 2491.
26 Crupi V, & Montanini R*, Int J Impact Eng,* 34 (2007) 509.
27 Omar M Y, Xiang C, Gupta N, Strbik O M & Cho K, *Mater Des*, 86 (2015) 536.
28 Yu J, Wang E, Li J & Zheng Z, *Int J Impact Eng*, 35 (2008) 885.
29 Krzyzak A, Mazur M, Gajewski M, Drozd K, Komorek A & Przybylek P, *Int J Aerospace Eng,* 4 (2016) 7816912.
30 Korim N S, Abdellah M Y, Dewidar M, & Abdelhaleem A M M, *Int J Sci Eng Res,* 6 (2015) 1221.
31 Chinthankumar D M, Jathin K J, Manujesh B J, Umashankar K S, & Prajna M R, *Am J Mater Sci,* 6 (2016) 77.
32 Voiconi T, Linul E, Marsavina L, Sadowski T, & Knec M , *Solid State Phenomena,* 216 (2014) 116.
33 Johnson F E A, Li Q M & Mines R A W, *J Cell Plast,* 44 (2008) 415.
34 Negi A, Rana V S, Kathait D S & Painuly H, *Int J Mathematics Phys Sci Res*, 3 (2015) 1.
35 Gabr M A, Gamsy R E & Latif M H A*, Int J Scientific Eng Res,* **7** (2016) 975.