Syntactic foam core metal matrix sandwich composite under bending conditions

Mohammed Yaseer Omar¹, Chongchen Xiang¹, Nikhil Gupta^{1,*}, Oliver M Strbik III², and Kyu Cho³

¹Composite Materials and Mechanics Laboratory, Mechanical and Aerospace Engineering Department, New York University, Polytechnic School of Engineering, 6 MetroTech Center, Brooklyn, NY 11201 USA

²Deep Springs Technology Inc. Toledo, OH 43615 USA

³U.S. Army Research Laboratory, Weapons and Materials Research Directorate, Aberdeen Proving Ground, MD 21005 USA

ABSTRACT

The present work aims at characterizing a metal matrix syntactic foam core sandwich composite under three-point bending conditions. The sandwich comprises alumina hollow particle reinforced A356 alloy syntactic foam with carbon fabric skins. Crack initiation in the tensile side of the specimen causing failure of skin, followed by rapid failure of core in the direction applied load, is observed as the failure mechanism. Crack propagation through the alumina particles is observed in the failed specimens instead of interfacial failure. The average maximum strength, flexural strain and stiffness were measured as 91.2 ± 5.6 MPa, 0.49 ± 0.06 % and 20.6 ± 0.7 GPa respectively. The collapse load is theoretically predicted using mechanics of sandwich beams. Experimental values show good agreement with theoretical predictions.

* Corresponding author, phone: +1-718-260 3080, Email: ngupta@nyu.edu

Keywords: Metal matrix composite; sandwich composite; syntactic foam; flexural properties.

1 INTRODUCTION

Metal foams are used in lightweight structures that are integral to a number of engineering applications such as ships, aircrafts and vehicles. Blast and ballistic armors, energy absorbers in vehicles, and heat exchangers are some of the examples where such materials can be useful [1-3]. It is difficult to control the size and shape of the pores in metal foams [4]. These concerns, coupled with the need for lightweight materials with higher stiffness and strength resulted in two distinct enhancing strategies. The first involves sandwiching metal foams between two stiff face-sheets, which allowed for a unique combination of energy absorption through large deformations within the core and an increased flexural strength through the face-sheets themselves [5, 6]. The second involves incorporating porosity through hollow particles instead of gas bubbles to provide a reinforcing effect to each pore and also to precisely control the size and volume fraction of porosity. Such hollow particle filled foams are called syntactic foams [7-9]. While these two developments are complementary, metal matrix syntactic foam core sandwich composites have not been fabricated or studied until now.

The stiff particles used as fillers are load bearing components of the microstructure, resulting in superior mechanical properties in syntactic foams [10, 11]. Additionally, material properties could now be tailored based on the choice of hollow particle material, wall thickness and volume fraction, providing additional variables to control and tailor the properties of syntactic foams [12-14]. Aluminum alloys (including A356, A380, 2014, 6061 and 7075) and Magnesium alloys (including AM20, AM50 and AZ91) have been commonly used as matrix metals [15]. Other

matrix materials include iron, zinc, steel and titanium [16-20]. To reinforce these matrices, hollow particles of glass, Al_2O_3 , SiC and fly ash have been used.

The flexural properties of sandwich structures, primarily involving metal foam cores, polymer syntactic foam cores and truss cores have been studied extensively. Studies on polymer matrix syntactic foam core sandwich composites have been conducted over two decades ago [21, 22]. Some of the relevant studies are summarized in Table 1 to provide an overview of the literature and a summary of material properties [15, 23-29]. Apart from mechanical properties, failure modes are extensively documented in these studies. Based on the reported results, metal matrix syntactic foam core sandwich composites can provide properties suitable for structural applications. However, such composites have not yet been studied.

Previous studies have provided a theoretical basis to determine the elastic deflection from the applied force during flexural testing [30]. Formulations include three and four point bending configurations with both flat indenters and cylindrical rollers. Although these assume that the face-sheets and core are homogenous, perfectly bonded and isotropic elastic-plastic solids, their predictions are often close to the experimental results.

Empirical and theoretical studies in the past have indicated that sandwich structures have competing failure mechanisms [29, 31, 32]. These include the face-yield mechanism (significant when the skins of a sandwich beam are made from a material of low yield strength and its yield therefore determines the limit load), the face-wrinkling mechanism (caused by an instability of the faces involving short wavelength elastic buckling of the upper face-sheet), the indentation

mechanism (caused by foams compressing with little transverse expansion) and the core shear mechanism (when the sandwich is subjected to a transverse shear force and it is carried primarily by the core). Theoretical models relating each of these mechanisms to a collapse load are often used as upper bound values in calculations. It is however, possible to calculate the collapse load of the composite beam using mechanics of composite beams.

The present study focuses on an A356 alloy matrix syntactic foam filled with Al_2O_3 hollow particles sandwiched between two carbon fabric face-sheets. Flexural properties and failure mechanisms are characterized for the sandwich composite in the present work. In the earlier work, compressive properties of this sandwich material were studied under quasi-static and high strain rate loading [33]. The study on compressive properties of this syntactic foam core sandwich composite included testing the material in both flatwise (fabric parallel to the loading platens) and edgewise (fabric layer parallel to the loading direction) orientations. In the flatwise orientation, failure is dominated by the characteristics of the core material and the effect of the presence of fabric layer is small. The failure initiated by cracking of weak particles, followed by deformation of surrounding matrix due to stress transfer to the matrix. In the edgewise orientation, failure initiated from the carbon fabric skins. Crushing of hollow particles into their own voids leads to densification of the material microstructure in both cases.

2 MATERIALS AND METHODS

2.1 Material

The core of the sandwich composite is made of A356 aluminum alloy filled with Al_2O_3 hollow spherical particles ($\text{Al}_2\text{O}_3\text{-HP}$). Figure 1 presents a solid model of the sandwich composite for

illustration. The $\text{Al}_2\text{O}_3\text{-HP}$ have an average diameter and wall thickness of 3 ± 0.22 mm and 105 ± 7 μm , respectively. Their true particle density is 0.87 g/cm^3 and the nominal tapped bulk density is 0.52 g/cm^3 . The carbon fabric in the face-sheets has a linear density of 0.193 kg/m^2 and is of a simple weave pattern. The specimen is fabricated with one layer of the carbon fabric on two opposite sides.

Figure 2 illustrates the pressureless infiltration technique used to fabricate the composite [33]. A carbon fabric layer is placed at the bottom of the mold cavity and then $\text{Al}_2\text{O}_3\text{-HP}$ are poured over it. A second carbon fabric layer is placed on top of the spheres before the mold is closed. The mold is then preheated to a temperature close to the melting point of the matrix alloy and held for a sufficient time to bring all contents to the same temperature. Thereafter, the mold is infiltrated with the matrix alloy melt through feed sprues and the gases are allowed to escape through vents. Once the mold is filled completely, the material is left to solidify. After solidification, the syntactic panel is removed from the mold and allowed to cool in a controlled oven.

2.2 Characterization methods

2.2.1 Flexural testing

Flexural testing is conducted in a three-point bending configuration using an Instron 4469 universal test system. Bluehill 2.0 software is used for data acquisition. The specimen orientation during bending tests is shown in Figure 3, where the face-sheets are located at the top and bottom surface of the specimen and are subjected to the maximum tensile and compressive forces. At least five specimens were tested and the average values of the measured properties and their

standard deviations are presented. The flexural strength (σ), flexural strain (ε_f) and the tangent modulus of elasticity (E_B) are calculated from the force-displacement curves using

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

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

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

where F , b , d and l refer to load (N), specimen width (mm), specimen thickness (mm) and support span (mm) respectively. Additionally, m , and D refer to the slope of the tangent to the initial straight line portion of the force-displacement graph and maximum deflection of the center of the beam (mm), respectively.

2.2.2 Microscopy

To obtain optical images of specimens, a Nikon D7000 DSLR camera equipped with an AF-S VR Micro-Nikkor 105mm f/2.8G IF-ED macro lens was used. Optical microscopy was conducted using a Nikon Epiphot 200 microscope fitted with a Nikon DS-Fil digital camera. The specimen preparation was conducted using standard metallographic procedures including grinding and polishing down to 1 μm slurry and etching using a solution of one part nitric acid in 20 parts alcohol.

A Hitachi S-3400N (Hitachi America Ltd., Tarrytown, NY) scanning electron microscope (SEM), equipped with secondary electron (SE) and back-scattered electron (BSE) detectors was also used for microstructure and failure analysis. The SEM specimens were sputter coated with gold using a Leica (Buffalo Grove, IL) sputtering unit.

3 RESULTS

3.1 Material microstructure

Figure 4(a) shows two $\text{Al}_2\text{O}_3\text{-HP}$ of the type used in the present sandwich composite. Figure 4(b) shows that the outer surface of the $\text{Al}_2\text{O}_3\text{-HP}$ has a high degree of surface roughness, which is useful in obtaining strong particle-matrix interfacial bonding. Apart from any chemical bonding effects, the rough surface is also expected to provide mechanical interlocking. Figure 4(c) shows a piece of a broken particle. It can be observed that the wall thickness is very small compared to the particle diameter. A small area on the cross section of the wall is marked with an arrow, which is further magnified in Figure 4(d). Sharp edges of the broken alumina particle surface are observed along with some micropores in the structure.

Figure 5(a) shows an optical micrograph and illustrates the continuous interface between the particles and the matrix. This shows good wetting between the particles and the matrix since there are no interfacial defects between closely spaced particles. The metal matrix is highlighted in Figure 5(b) where an aluminum-rich dendritic structure can be observed surrounded by needle-like Al-Si precipitates. A356 alloy primarily contains about 7 wt.% Si in Al. The Al-Si binary phase diagram is eutectic. As observed in the microstructure, the first solidifying phase has very low Si content and the last solidifying phase has the eutectic composition, which contains about 12.6 wt.% Si. These features can be found in the microstructure.

Figure 5(c) shows an optical micrograph of the carbon fabric within the matrix. The high magnification SEM micrograph in Figure 5(d) shows the cross-section of the fabric and that the

matrix has completely infiltrated the fabric and has surrounded each fiber. Extensive microscopy revealed complete infiltration of the particle bed and skin layer with the melt and no manufacturing defects in the sandwich. Previous studies available on aluminum alloy-carbon fiber composites have observed the formation of an Al_4C_3 brittle phase around the carbon fibers [34]. Detailed investigations found that the direction of applying load with respect to the Al_4C_3 needles have a strong effect on the measured mechanical properties. The extent of Al_4C_3 formation was found to be dependent on the crystallinity of the carbon fibers and on the time of contact between aluminum alloy melt and carbon fibers [35].

3.2 Flexural Test

A representative stress-strain curve obtained in the flexural testing of the syntactic foam core sandwich composite is shown in Figure 6(a). The curve shows an initial linear elastic region. The stress drops drastically after reaching a peak. The peak corresponds to the failure of the skin on the tensile side of the specimen. Several images illustrating the failure sequence of this specimen are shown in Figure 6(b1-b5); the locations of these observations are marked on the stress-strain graph. The initial test configuration is shown in Figure 6(b1). Figure 6(b2) shows that there is no damage within the elastic deformation region. Figure 6(b3) shows that at the compressive strength, the crack (marked by a circle) initiates on the tensile side of the specimen. Since the fabric is stronger than the matrix and is load bearing on the tensile side, the fabric failure leads to a transfer of load to the core, which results in rapid crack growth in the syntactic foam core. The crack growth results in stress relief in the material and reduces the load significantly, Figure 6(b4). Factors such as localized concentration of alumina particles and the presence of any

defects in the particles or matrix close to the fabric layer contribute in determining the location of crack initiation. When the crack propagates across the core thickness (Figure 6(b5)), the load is now transferred to the second skin. The progressive failure of the top face-sheet fabric reduces the rate of stress drop and provides additional strain before failure. Interfacial separation between core and face-sheets is not observed in this material. Interfacial failure is a common occurrence in sandwich composites under the influence of shear stresses [27]. Further tailoring of the sandwich can be conducted by optimizing the number of fabric layers in the skin, fabric type and core to skin thickness ratio.

The flexural strength is defined as the peak after the elastic region of the stress-strain curve and the corresponding strain is defined as the flexural strain. The modulus is calculated as the slope in the elastic region. The average flexural strength, flexural strain and modulus are measured to be 91.2 ± 5.6 MPa, 0.49 ± 0.06 % and 20.06 ± 0.7 GPa respectively.

Failure analysis was conducted on the specimens after the bending test. Figure 7(a) shows the locations of SEM observations on the failure surface of a specimen. It is observed in Figure 7(b-f) that the crack propagates through the $\text{Al}_2\text{O}_3\text{-HP}$. Signs of crack bowing around the particles or interfacial failure are not observed in these micrographs. It is also observed that the brittle $\text{Al}_2\text{O}_3\text{-HP}$ develop numerous other cracks as well, which is likely due to the difference in failure strain of the particle material and the matrix material. The crack propagation across the core depends on the weakest path under the middle loading anvil. In some cases the crack may be slightly offset because of the localized structure of the composite. In such cases, it is observed to travel to the anvil near the interface of the top skin and the core. The failure at the top interface is further magnified in Figure 8. Transition of the crack from core to the face-sheet can be observed in

Figure 8(a). The dotted circle denotes the location of top loading anvil. Face-sheet wrinkling is observed near the top anvil and is marked with an arrow in Figure 8(a). Figure 8(b-c) show the fiber buckling in the region of face-sheet wrinkling. The wrinkling is in the outward direction because of stiff core present in the sandwich. The face-sheet wrinkling under compression is also observed in polymer matrix syntactic foam core sandwich composites [36].

3.3 Analytical Predictions

The following beam theory (adapted from Allen *et al.* [37]) assumes that the core and face-sheets of the sandwich composites are homogenous. Figure 3 illustrates a sandwich beam of span l , width b , core thickness H , homogenous face-sheets of thickness t_f , an overhang of s and is supported by cylindrical rollers of radius R spaced a distance l with a load F applied to the top of a cylindrical loading anvil of radius R . The moduli of the face-sheets and the core material are E_f and E_c respectively.

It is well known however, that parameters related to the carbon fabric face-sheets should be treated cautiously. The mechanical properties are known to degrade in the presence of a multi-axial stress states such as those imposed beneath a loading roller; therefore the face-sheet beneath the loading roller has been neglected in calculations [29, 38]. The relative deflection δ of the central roller with respect to the supports is given by

$$\delta = \frac{Fl^3}{48(EI)} + \frac{Fl}{4(AG)} \quad (4)$$

where flexural rigidity, (EI) is calculated by

$$(EI) = \frac{E_f b t_f^3}{12} + \frac{E_f b t_f d^2}{4} + \frac{E_c b H^3}{12} \quad (5)$$

and d is the total thickness of the sandwich. The panel rigidity, (AG) is defined as

$$(AG) = \frac{G_c d^2 b}{H} \quad (6)$$

where G_c is the core shear modulus. The core shear modulus is determined by

$$G_c = \frac{E_c}{2(1+\nu)} \quad (7)$$

where the core modulus, E_c was taken to be 4.15 GPa [39] and its Poisson's ratio was assumed to be that of aluminum [40]. Using the relevant input parameters, the theoretical, linear force-displacement relationship was determined.

In the analysis of sandwich beams, strength is a factor taken into consideration alongside stiffness. Calculating the peak force attained after the elastic region for a sandwich beam involves understanding the collapse mechanisms. Four main collapse modes have been identified for three point bending with cylindrical rollers: the face yield, wrinkling of the compressive face-sheet, core shear and indentation collapse modes. These mechanisms have been studied and verified extensively in the literature [41-47]. Since these calculations offer theoretical upper-bound estimates for the collapse load, mechanics of a composite beam [48] are employed instead. Transformation is used to convert the beam of two different materials into one of varying cross-section widths using

$$\bar{y} = \frac{A_1 \bar{y}_1 + n A_2 \bar{y}_2}{A_1 + n A_2}, \quad n = \frac{E_f}{E_c} \quad (8)$$

$$I_t = I_1 + n I_2 \quad (9)$$

$$\sigma_{f,\max} = \frac{n M c}{I_t} \quad (10)$$

$$M = \frac{P}{2} \times \frac{l}{2} \quad (11)$$

The cross-section of the composite beam is shown in Figure 9, the dotted line indicates the centroid axis calculated by Equation (8) when the top face-sheet is not taken into consideration. Equation (9) is used to calculate the total moment of inertia and Equation (10) is re-arranged to find the maximum moment M , acting on the beam. To find the collapse load, Equation (11) is used. The moment is found using the reaction force at the support (half of force of the loading anvil, P) and the distance from the support to the loading anvil (half of the support span, l). The final collapse load is given as 1782 N.

A comparison of the theoretical predictions and a representative experimental result is shown in Figure 10 and they show reasonable agreement, given the possibility of having cracks in hollow particles and other possible inhomogeneities in the sandwich. Studies have shown that although aluminum composites employing carbon fiber in other configurations have had excellent strength and stiffness, they were lower than expected. Degradation of mechanical properties was found to occur during manufacturing processes because of chemical reactions at the fiber-matrix interfaces and weakening of the fibers [49, 50]. Despite the observations that the fibers are wetted and surrounded by matrix, it is expected that some degradation of fibers would take place during the infiltration process and will result in lower than expected strength of the composite. In general, success in fabricating metal matrix syntactic foam core sandwich composites paves the way for future studies to further optimize the structure and properties of such composites for specific applications and loading conditions.

4 CONCLUSIONS

The present study presents the first attempt on fabrication of metal matrix syntactic foam core sandwich composites. The fabricated Al alloy A356 matrix Al_2O_3 hollow particle reinforced syntactic foam core metal matrix sandwich composite contained carbon fabric reinforced face-sheets and is tested under three point bending conditions. The main conclusions can be summarized as follows:

- The average maximum stress, flexural strain and stiffness of the metal matrix syntactic foam core sandwich composite are measured as 91.2 ± 5.6 MPa, 0.49 ± 0.06 % and 20.6 ± 0.7 GPa, respectively.
- Failure mechanism indicates that the fracture is initiated in the tensile side of a specimen in three point bending. The crack rapidly propagates to the compressive side of the specimen and ultimately leads to failure. There is no evidence of crack tip blunting or bowing, indicating strong particle-matrix interfacial bonding.
- Experimental evidence shows reasonable agreement with the calculations for sandwich composites that assumes the core and the face-sheets are monolithic and that the effect of the top sheet under compressive stress is negligible. The experimental collapse load is lower than the theoretical prediction because of the possible degradation of the face-sheets during the fabrication process.

ACKNOWLEDGMENTS

This research is sponsored by the U.S. Army Research Laboratory contract W911NF-10-2-0084 of DST and the Cooperative Agreement W911NF-11-2-0096 with NYU. Partial support from NSF grant IIA-445686 is also acknowledged. The authors acknowledge scholarship from the

NYUAD Vice Chancellor's office to Mohammed. Dr. Dung Dinh Luong, and Steven E. Zeltmann are thanked for help during the research work.

The views and conclusions contained in this paper are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the ARL or the U.S. Government unless so designated by other authorized documents.

REFERENCES

1. Qin, Q. and T.J. Wang, *Low-velocity impact response of fully clamped metal foam core sandwich beam incorporating local denting effect*. Composite Structures, 2013. **96**: p. 346-356.
2. Garcia-Avila, M., M. Portanova, and A. Rabiei, *Ballistic performance of composite metal foams*. Composite Structures, 2015. **125**: p. 202-211.
3. Odabae, M. and K. Hooman, *Application of metal foams in air-cooled condensers for geothermal power plants: An optimization study*. International Communications in Heat and Mass Transfer, 2011. **38**(7): p. 838-843.
4. Jiang, W., S.S. Sundararam, and W. Li, *Fabrication of microcellular metal foams with sphere template electrodeposition*. Manufacturing Letters, 2014. **2**(4): p. 118-121.
5. Qin, Q.-h., et al., *Indentation of sandwich beams with metal foam core*. Transactions of Nonferrous Metals Society of China, 2014. **24**(8): p. 2440-2446.
6. Rajaneesh, A., I. Sridhar, and S. Rajendran, *Relative performance of metal and polymeric foam sandwich plates under low velocity impact*. International Journal of Impact Engineering, 2014. **65**: p. 126-136.

7. Myers, K., et al., *Structure property relationship of metal matrix syntactic foams manufactured by a binder jet printing process*. Additive Manufacturing, 2015. **5**: p. 54-59.
8. Orbulov, I.N., *Compressive properties of aluminium matrix syntactic foams*. Materials Science and Engineering: A, 2012. **555**: p. 52-56.
9. Orbulov, I.N., *Metal matrix syntactic foams produced by pressure infiltration—The effect of infiltration parameters*. Materials Science and Engineering: A, 2013. **583**: p. 11-19.
10. D.P. Mondal, N.J., Anshul Badkul, S. Das, Raghavendra Khedle, *High temperature compressive deformation behaviour of aluminum syntactic foam*. Material Science and Engineering, 2011. **534**(2): p. 521-529.
11. Orbulov, I.N. and J. Ginzstler, *Compressive characteristics of metal matrix syntactic foams*. Composites Part A: Applied Science and Manufacturing, 2012. **43**(4): p. 553-561.
12. Taherishargh, M., et al., *On the particle size effect in expanded perlite aluminium syntactic foam*. Materials & Design, 2015. **66, Part A**: p. 294-303.
13. Yu, M., P. Zhu, and Y. Ma, *Experimental study and numerical prediction of tensile strength properties and failure modes of hollow spheres filled syntactic foams*. Computational Materials Science, 2012. **63**: p. 232-243.
14. Gupta, N. and W. Ricci, *Comparison of compressive properties of layered syntactic foams having gradient in microballoon volume fraction and wall thickness*. Materials Science and Engineering: A, 2006. **427**(1–2): p. 331-342.
15. Pradeep K. Rohatgi, N.G., Benjamin F. Schultz, and Dung D. Luong, *The Synthesis, Compressive Properties, and Applications of Metal Matrix Syntactic Foams*. JOM, 2011. **63**(2): p. 36-42.

16. Luong, D.D., et al., *Quasi-static and high strain rates compressive response of iron and Invar matrix syntactic foams*. Materials & Design, 2015. **66, Part B**: p. 516-531.
17. Mondal, D.P., et al., *Titanium-cenosphere syntactic foam made through powder metallurgy route*. Materials & Design, 2012. **34**: p. 82-89.
18. Daoud, A., *Synthesis and characterization of novel ZnAl₂₂ syntactic foam composites via casting*. Materials Science and Engineering: A, 2008. **488**(1–2): p. 281-295.
19. Peroni, L., et al., *Investigation of the mechanical behaviour of AISI 316L stainless steel syntactic foams at different strain-rates*. Composites Part B: Engineering, 2014. **66**: p. 430-442.
20. Lehmhus, D., et al., *Quasi-static and Dynamic Mechanical Performance of Glass Microsphere- and Cenosphere-based 316L Syntactic Foams*. Procedia Materials Science, 2014. **4**: p. 383-387.
21. Hiel, C., D. Dittman, and O. Ishai, *Composite sandwich construction with syntactic foam core: A practical assessment of post-impact damage and residual strength*. Composites, 1993. **24**(5): p. 447-450.
22. Ishai, O., C. Hiel, and M. Luft, *Long-term hygrothermal effects on damage tolerance of hybrid composite sandwich panels*. Composites, 1995. **26**(1): p. 47-55.
23. Deshpande, V.S. and N.A. Fleck, *Collapse of truss core sandwich beams in 3-point bending*. International Journal of Solids and Structures, 2001. **38**(36–37): p. 6275-6305.
24. Russell, B.P., et al., *Quasi-Static three-point bending of carbon fiber sandwich beams with square honeycomb cores*. Journal of Applied Mechanics, 2011. **78**(2): p. 1-15.

25. Mohan, K., et al., *Failure of sandwich beams consisting of alumina face sheet and aluminum foam core in bending*. Materials Science and Engineering: A, 2005. **409**(1–2): p. 292-301.
26. Wan, L., et al., *Fabrication and interfacial characterization of aluminum foam sandwich via fluxless soldering with surface abrasion*. Composite Structures, 2015. **123**: p. 366-373.
27. Gupta, N. and E. Woldeesenbet, *Characterization of flexural properties of syntactic foam core sandwich composites and effect of density variation*. Journal of Composite Materials, 2005. **39**(24): p. 2197-2212.
28. Manalo, A.C., et al., *Flexural behaviour of structural fibre composite sandwich beams in flatwise and edgewise positions*. Composite Structures, 2010. **92**(4): p. 984-995.
29. Steeves, C.A. and N.A. Fleck, *Collapse mechanisms of sandwich beams with composite faces and a foam core, loaded in three-point bending. Part I: analytical models and minimum weight design*. International Journal of Mechanical Sciences, 2004. **46**(4): p. 561-583.
30. Gibson, R.F., *Principles of composite material mechanics*. 2011: CRC press.
31. Crupi, V. and R. Montanini, *Aluminium foam sandwiches collapse modes under static and dynamic three-point bending*. International Journal of Impact Engineering, 2007. **34**(3): p. 509-521.
32. Li, M., et al., *Structural design of pyramidal truss core sandwich beams loaded in 3-point bending*. Journal of Mechanics of Materials and Structures, 2012. **6**(9): p. 1255-1266.
33. Omar, M.Y., et al., *Syntactic foam core metal matrix sandwich composite: Compressive properties and strain rate effects*. Materials Science and Engineering: A.

34. Xu, W., et al., *Interfacial microstructure and growth mechanism of Al₄C₃ in Grf/Al composites fabricated by liquid pressure method*. Micron, 2014. **65**: p. 10-14.
35. I.N. Orbulov, A.N., J. Dobranszky, *XRD and EDS Investigations of Metal Matrix Composites and Syntactic Foams*. EXRS 2008 Proceedings: 13th European Conference on X-Ray Spectrometry, Cavtat, Dubrovnik, Croatia. Editors: S. Fazinić, M. Jaksic, (16-20 June 2008): p. Paper number: PB-51.
36. Gupta, N., et al., *Response of Syntactic Foam Core Sandwich Structured Composites to Three-Point Bending*. Journal of Sandwich Structures and Materials, 2002. **4**(3): p. 249-272.
37. Allen, H.G., *Theory of Sandwich Beams and Plates (Volume 1: Fundamental Aspects)*, in *Composite Materials in Maritime Structures*, R.A. Shenoi and J.F. Wellicome, Editors. 1993, Cambridge University Press, NY. p. 205-235.
38. Budiansky, B. and N.A. Fleck, *Compressive failure of fibre composites*. Journal of the Mechanics and Physics of Solids, 1993. **41**(1): p. 183-211.
39. Licitra, L., et al., *Dynamic properties of alumina hollow particle filled aluminum alloy A356 matrix syntactic foams*. Materials & Design, 2015. **66, Part B**: p. 504-515.
40. Kohlhauser, C. and C. Hellmich, *Determination of Poisson's ratios in isotropic, transversely isotropic, and orthotropic materials by means of combined ultrasonic-mechanical testing of normal stiffnesses: Application to metals and wood*. European Journal of Mechanics - A/Solids, 2012. **33**: p. 82-98.
41. Zenkert, D., *An introduction to sandwich construction*. 1997: Engineering materials advisory services.

42. Gibson, L.J. and M.F. Ashby, *Cellular solids: structure and properties*. 1997: Cambridge university press.
43. Chen, C., A. Harte, and N. Fleck, *The plastic collapse of sandwich beams with a metallic foam core*. International Journal of Mechanical Sciences, 2001. **43**(6): p. 1483-1506.
44. Triantafillou, T.C. and L.J. Gibson, *Failure mode maps for foam core sandwich beams*. Materials Science and Engineering, 1987. **95**: p. 37-53.
45. Triantafillou, T.C. and L.J. Gibson, *Minimum weight design of foam core sandwich panels for a given strength*. Materials Science and Engineering, 1987. **95**: p. 55-62.
46. Lingaiah, K. and B. Suryanarayana, *Strength and stiffness of sandwich beams in bending*. Experimental Mechanics, 1991. **31**(1): p. 1-7.
47. Theotokoglou, E.E., *Analytical determination of the ultimate strength of sandwich beams*. Applied Composite Materials, 1996. **3**(5): p. 345-353.
48. Ugural, A.C. and S.K. Fenster, *Advanced strength and applied elasticity*. 2003: Pearson education.
49. Chung, D.D.L., *Carbon fiber composites*. 2012: Butterworth-Heinemann.
50. Cheng, H.M., et al., *The tensile strength and fiber degradation of carbon fiber reinforced aluminium composites*. Scripta Metallurgica et Materialia, 1991. **25**(8): p. 1951-1956.

FIGURE CAPTIONS

Figure 1. CAD model of syntactic foam core sandwich composite. The skins (or face-sheets) are made of carbon fabric. In this image the matrix material is made transparent to demonstrate the random orientation of particles inside the material. The model is not drawn to scale.

Figure 2. Schematic representation of sandwich composite fabrication method using pressureless infiltration process.

Figure 3. Three-point bend test configuration and specimen dimensions.

Figure 4. (a) Scanning electron micrograph of hollow alumina particles, (b) high surface roughness on outer surface of the particle, (c) a piece of a broken alumina particle; the cross section marked on the sidewall of the piece with an arrow is magnified in (d), where some micropores are observed on the fracture surface.

Figure 5. (a) Optical micrograph shows the matrix region between three alumina hollow particles, (b) optical micrograph showing the matrix microstructure, (c) optical micrograph showing carbon fibers within a face-sheet and (d) higher magnification scanning electron micrograph of carbon fibers showing clean interface between fibers and the matrix.

Figure 6. (a) Representative stress-strain curve of flexural testing of a metal matrix sandwich composite. (b1-b5) Images of specimens during various phases of deformation: (b1) initial specimen, (b2) elastic region, (b3) specimen at the flexural strength, (b4) during stress drop and crack propagates through core and (b5) load is now taken by the top face-sheet.

Figure 7. Propagation of crack from the tensile to the compression side of the specimen is progressively captured in (a) – (e). (f) Locations of the acquired images are marked on the specimen.

Figure 8. Fractured skin on the compression side of the sandwich composite.

Figure 9. Cross-section of composite beam used in collapse mode calculation.

Figure 10. Theoretical prediction vs. experimental results for three-point bend test.

Table 1. Existing relevant studies on syntactic foams and sandwich composites.

Reference	Syntactic Foam	Mechanical Testing	Results
Rohatgi <i>et al.</i> [15]	General review of metal matrix syntactic foams	Review Paper	(1) Three methods of MMSF synthesis: (a) pressure infiltration, (b) stir casting and (c) powder metallurgy (2) Interfacial reactions may cause brittle phases that can be detrimental to mechanical properties in AMSFs.
Deshpande <i>et al.</i> [23]	Truss cores with either solid or triangulated face-sheets. Cast in aluminum-silicon alloy and silicon brass	Flexural: (1) Three-point bend.	(1) Collapse is by four competing mechanisms: face-yield, face-wrinkling, indentation and core shear. (2) Truss core sandwich beams are lighter and compete with metallic foam cores.
Russell <i>et al.</i> [24]	Carbon fiber sandwich beams with square honeycomb cores	Flexural: (1) Quasi-static three point bending.	(1) Analytical expressions for competing collapse mechanisms were derived: core shear, face microbuckling, face wrinkling and indentation.
Mohan <i>et al.</i> [25]	Aluminum foam core with alumina face-sheets	Flexural: (1) Four-point bend tests	(1) Competing failure modes identified include core indentation, face-sheet cracking and core shear. (2) Analytical models for each were in good agreement with experimental evidence.
Wan <i>et al.</i> [26]	Aluminum foam core with aluminum plate sheets	Flexural: (1) Three-point bend tests	(1) Three failure modes observed: indentation, core shear and plastic hinging. (2) Vibrations in fluxless soldering method affect bending strength: the higher the frequency, the higher the bending strength.
Gupta <i>et al.</i> [27]	Epoxy matrix with glass microballoons and glass fabric (plain weave)	Flexural: (1) Three-point bend (2) Four-point bend (3) Short beam shear (SBS)	(1) Core shear and skin bending stress in three and four point bend tests not affected by microballoon radius ratio η . (2) In SBS tests, core shear and skin bending stresses decrease with smaller specimen aspect ratio. (3) Fracture originates on tensile side during three point bend test.
Manalo <i>et al.</i> [28]	Toughened phenol formaldehyde resin matrix with glass fiber composite skins	Flexural: (1) Four-point bend	(1) Brittle-type failure occurred in the flatwise orientation. In edgewise orientation, presence of skins increased ultimate strength.
Steeves <i>et al.</i> [29]	Theoretical study of collapse mechanisms of sandwich beams loaded in three-point bending	Flexural: (1) Three-point bend	(1) Analytical expressions for force-displacement curves of sandwich composites are shown.

Figure 1. CAD model of syntactic foam core sandwich composite. The skins (or face-sheets) are made of carbon fabric. In this image the matrix material is made transparent to demonstrate the random orientation of particles inside the material. The model is not drawn to scale.

Figure 2. Schematic representation of sandwich composite fabrication method using pressureless infiltration process.

Figure 3. Three-point bend test configuration and specimen dimensions.

Figure 4. (a) Scanning electron micrograph of hollow alumina particles, (b) high surface roughness on outer surface of the particle, (c) a piece of a broken alumina particle; the cross section marked on the sidewall of the piece with an arrow is magnified in (d), where some micropores are observed on the fracture surface.

Figure 5. (a) Optical micrograph shows the matrix region between three alumina hollow particles, (b) optical micrograph showing the matrix microstructure, (c) optical micrograph showing carbon fibers within a face-sheet and (d) higher magnification scanning electron micrograph of carbon fibers showing clean interface between fibers and the matrix.

(a)

(b1)

(b2)

(b3)

(b4)

(b5)

Figure 6. (a) Representative stress-strain curve of flexural testing of a metal matrix sandwich composite. (b1-b5) Images of specimens during various phases of deformation: (b1) initial specimen, (b2) elastic region, (b3) specimen at the flexural strength, (b4) during stress drop and crack propagates through core and (b5) load is now taken by the top face-sheet.

Figure 7. Propagation of crack from the tensile to the compression side of the specimen is progressively captured in (a) – (e). (f) Locations of the acquired images are marked on the specimen.

Figure 8. Fractured skin on the compression side of the sandwich composite.

Figure 9. Cross-section of composite beam used in collapse mode calculation.

Figure 10. Theoretical prediction vs. experimental results for three-point bend test.

Graphical Abstract