ELASTIC BENDING BEHAVIOUR OF SANDWICH COMPOSITE STRUCTURES WITH ABS CORES BY USING ADDITIVE MANUFACTURING

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Abstract - Maintaining the lightweight performance of sandwich structures while achieving good bending strength and stiffness is difficult. These programmable sandwich constructions use 3D printed core materials with hexagonal honeycomb, re-entrant honeycomb, and circular honeycomb topologies with varying core densities. Three-point bending tests are conducted to determined the bending strength and stiffness of these sandwich composites including an Acrylonitrile Butadiene Styrene core and a unidirectional carbon fibre reinforced polymer face sheet. The sandwich composite with the greater relative core density displays greater bending strength and stiffness than the composite with the lower relative core density. The sandwich composites beam with re-entrant honeycomb core exhibit the strongest bending strength and stiffness due to negative Poisson's ratio. Experiments reveal that designed core structures can be sued to regulate bending qualities. These results provide characteristics for a broad variety of industrial and structural applications.

Keywords - Sandwich Beam, Honeycomb Core, Bending, Lightweight Structure.

I. INTRODUCTION

Sandwich structures are presently widely employed as low weight components in the airplane, automobile, and civil engineering sectors due to their excellent bending stiffness and energy absorption characteristics [1]. A structure is typically made up of three substructures. The outer most layer is made up of a thin layer that seeks to disperse burst pressure more equally across the second and third substructures known as the bonding layer and core, respectively. Several studies have found that component materials, geometrical parameters, and core cell design have a significant impact on mechanical performance [2,3].Sandwich constructions were often exposed to bending forces in engineering applications. As a consequence, bending behaviour, including bending stiffness and strength is critical in practical applications. Additive manufacturing is becoming increasingly popular for both research and industry applications. One of the advantages of 3D printing was the ability to create intricate components and products in combinations that would otherwise be unattainable [4].Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are the most often used materials in 3D printing. Compared to other thermoplastics, ABS has higher resistance to bending and elongation before breaking. PLA is praised for flexibility, while ABS is praised for its toughness [5]. In particular, lightweight alternative materials such as aluminium, magnesium alloy, and composite materials are being used in engineering applications to reduce the weight and enhance the rigidity of the final product. Carbon fibre reinforced polymers, a typical lightweight material with particular strength and stiffness superior to metals, is believed to be the material that will eventually replace traditional metals in the construction industry. A prepreg fabric structure and stacking sequences are often responsible for determining the mechanical characteristics of carbon fibre reinforced polymer products such as tensile strength and bending stiffness, as well as other qualities [6-8]. Honeycomb structures have seen greater application because to the growing need for lightweight and performance-based materials in the structural domain [9]. It can bee seen that the core cell's geometric configuration and the mechanical properties of the core fabric were used to define the straight elastic behaviour of typical honeycombs [10]. Li, et al. [11] investigated the mechanical properties of honeycomb cores with a negative Poisson's ratio, which included a chiral truss and re-entrant honeycomb, in order to better understand the behaviour. It has been demonstrated that auxetic lattice reinforced composites outperform non-auxetic lattice reinforced composites in terms of mechanical performance. The major criteria determining flexure characteristics, according to prior study, are face sheet thickness, honeycomb height, and honeycomb orientation [12]. Gao, et al. [13] developed fully thermoplastic honeycomb sandwich structures made of continuous glass fibre reinforced polypropylene face sheets, a polypropylene core, and a thermoplastic film assembly. Meanwhile, the ply sequence and the thickness of the face sheet had the largest impact on the failure modes, which were mostly Li and Ma in incidence [12,13]. According to certain research, the sandwich beam's bending characteristics are influenced by the core topologies.

A vast number of experiments have been carried out in order to understand the complexity of core designs and topologies. However, there is a scarcity of data on the bending behaviour of sandwich

constructions with honeycomb cores composed of thermoplastic materials acrylonitrile butadiene styrene. The effect of sandwich core geometric arrangement on bending behaviour is unknown. To design these materials in variety applications, knowing their bending behaviour is crucial. Consequently, this paper examined the bending behaviour of sandwich structures with various core topologies and various relative core densities by using three-point bending test. This including the re-entrant honeycomb core, hexagonal honeycomb core, and circular honeycomb core, where the honeycomb core materials are acrylonitrile butadiene styrene, which was manufactured using additive manufacturing technique, and unidirectional carbon fibre reinforced polymer is considered as the face sheet material.

II. THEORETICAL BACKGROUND

Bending stiffness is a property that indicates how well it resists deformation in response to an applied force. The stiffness, k, is defined as shown below.

$$k = \frac{P}{\delta} \tag{1}$$

The parameters P signify the applied force and δ denoted the member's deformation in the direction of the applied force.

For sandwich beam in three-point bending, the elastic analysis is outlined here. Suppose a sandwich beam of span L and width W loaded in three points bending with a central load P. Because of the interplay between material qualities and geometric dimensions, the bending properties of sandwich structures are highly dependent on their construction. D, the equivalent bending stiffness of a sandwich beam, was explored in order to better understanding its bending properties. It is assumed that the skins stay securely attached to the core, the beams cylindrically with no curvature in the yz plane, and that cross sections remain parallel to the beam's longitudinal axis [14,15]. As a result, D is simply obtained as shown below.

$$D = D^1 + D^2 = \frac{E_f W f^3}{6} + \frac{E_f W f d^2}{2} + \frac{E_c W h^3}{12} \tag{2}$$

The bending stiffness is comprised of two components, as shown in Equation 2. The first is the face-sheets contribution. Sandwich core is responsible for the second contribution. E_f and $E_c$signify the face-sheet's and sandwich core's elastic modulus, respectively.

Bending strength is critical for evaluating the bending behaviour of sandwich beams, since this directly influences the products service life. Calculation of bending strength, σ_s, may be conducted using the simplified beam model [16]. Bending strength was determined as follows.

$$\sigma_s = \frac{3P_m L_s}{2WH^2} \tag{3}$$

The parameter P_m denotes the maximum load in three-point bending and L_s denotes the span distance.

III. EXPERIMENTAL PROGRAM

3.1 Raw Materials

The Unidirectional Carbon Fibre Reinforced Polymer (U-CFRP) plateis provided by XC Carbon Fibre Company Limited (Guangdong, China), and the thickness is1 mm. The unidirectional carbon fibre reinforced polymer plate is processed by hot press one layer by one layer of carbon fibre cloth T300. This type of carbon fibre reinforced polymer plates is employed as a portion of the sandwich structure's face sheet. The honeycomb core structure is made of Acrylonitrile Butadiene Styrene (ABS). Various honeycomb structures were manufactured from Acrylonitrile Butadiene Styrene by the additive manufacturing process supplied by Harn Engineering Solutions Public Company Limited (Bangkok, Thailand). Epoxy resin is chosen as the adhesive. This type of epoxy glue has twelve-hour cure time at room temperature and a gel time of ten to fifteen minutes to precisely position.

3.2 Honeycomb Core Cell Design

The geometric aspects of the planned sandwich design philosophy hexagonal honeycomb, re-entrant honeycomb, and circular honeycomb are addressed in this section. The schematic of three lattice microstructures is shown in Figure 1a, b, and c, respectively. Each configuration's relative density (ρ^*/ρ_s) can be determined as follows:

For hexagonal honeycombs [17],

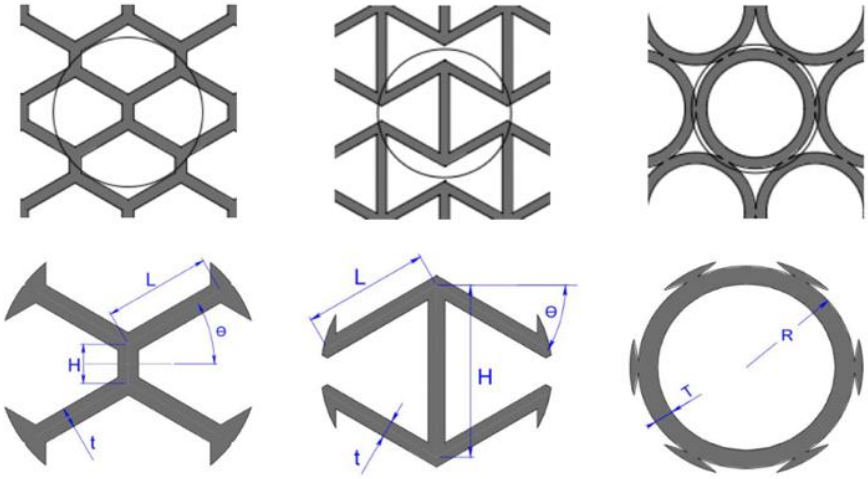
$$\frac{\rho^*}{\rho_s} = \frac{(t/L)[(H/L)+2]}{2cos\theta\,[(H/L)+sin\theta\,]} \tag{4}$$

For re-entrant honeycombs [17],

$$\frac{\rho^*}{\rho_s} = \frac{(t/L)[(H/L)+2]}{2cos\theta\,[(H/L)+sin\theta\,]} \tag{5}$$

For circular honeycombs [18],

$$\frac{\rho^*}{\rho_s} = \frac{(T/R)[1-(T/2R)]\pi}{\sqrt{3}} \tag{6}$$



(a) (b) (c)

Figure 1: The schematic of three lattice structures: (a) hexagonal honeycomb; (b) re-entrant honeycomb; (c) circular honeycombs.

In this study, relative densities of 0.3 and 0.5 are taken into account. The relative density can be varied by altering the thickness of the cell wall of each honeycomb structure, three types of cellular structures are configured to have the same unit cell dimension of 16 x 16 mm. Therefore, the thickness of cell walls in each arrangement may be determined using Equation (4), (5), and (6). Table 1 details the parameters for each lattice structure.

$\frac{\rho^*}{\rho_s}$	Hexagonal				Re-entrant				Circular	
	L	H	t	θ	L	H	t	θ	T	R
0.3	9.24	3.38	1.76	30°	9.24	12.62	1.23	30°	1.45	8
0.5	9.24	3.38	2.92	30°	9.24	12.62	2.06	30°	2.64	8

Table 1: Design parameter of hexagonal, re-entrant and circular honeycombs (unit in mm).

3.3 Preparation of Three Point Bending Test Specimens

The bending test specimens are manufactures according to ASTM C393 standard. The unidirectional carbon fibre reinforced polymer plate was cut using the waterjet. After all the face sheets and core material have been completed, epoxy resin is used to join two face sheets to one core structure at room temperature by applying the pressure. All specimens are maintained attached for one day to ensure that they are adhesively linked, then dried for three days to enables coherent between the core and the face sheets. The surfaces and the sides of the sandwich skins are then cleaned to eliminate the influence of leftover glue. The sandwich beams are designed to have overall dimensions of 200 mm x 75 mm x 12mm. The schematic of the sandwich beam is shown in Figure 2. Table 2 show the parameters of the three points bending test specimen. H is short for hexagonal honeycomb, R is short for re-entrant honeycomb and C is short for circular honeycomb. The number followed H, R and C mean the relative density of the core where number 1 stand for the relative density at 0.3 and 2 stand for the relative density at 0.5. U stand for unidirectional carbon fibre reinforced polymer plate. For instance, H2U means the sandwich beam with hexagonal honeycomb core with relative density at 0.5 and unidirectional carbon fibre reinforced polymer face sheets.

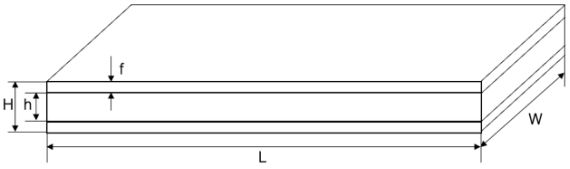


Figure 2: The schematic of the sandwich beam

Parameters	Value
Length, L	200
Width, W	75
Face sheet thickness, f	1
Core thickness, h	10
Total thickness without bonded layer, H	12

Table 2. Parameters of three point bending test specimens (unit in mm).

3.4 Specimen Inspection

Prior to printing, the mass of the honeycomb core was calculated using the programme. The relative core density of 0.3, based on the design of the core, should weigh 76 grammes. Despite having a relative density of 0.5, the core should have weighed 112 grammes. After the honeycomb cores were printed, they were weighed by using the digital scale to ascertain their actual mass. Table 3 contains the values of the specimens. It is evident that the masses of all cores were almost identical to the design. All

cores that are 3D printed must be flat and parallel. This is established by putting the core on the levelled table and verifying there is no space between the table and the core. After applying epoxy to adhere the core to the face sheets, the weight of the sandwich beam was measured for checking the excessive amount of epoxy inside the core. In addition, the thickness of sandwich beams was measured at six positions by using the digital vernier caliper, and the average thickness and standard deviation were determined as shown in Table 3. According to the patterns shown in Table 2, the thickness of the specimen without bonded layer was 12 mm. Therefore, the thickness of bonded layer can be determined. However, the non-uniform thickness of the epoxy layer will affect the standard deviation of the specimen.

3.5 Tensile Test

In order to clearly identify the material properties and to facilitate further research, the loading programme for the tensile test on carbon fibre reinforced polymers and acrylonitrile butadiene styrene is performed based on the American Society for Testing and Materials standard test protocol. Tensile testing according to ASTM D3039 is used to determine the force necessary to fracture a polymer composite specimen and the extent to which the specimen stretches or elongates to the breaking point. The ASTM D3039 standard specimens are subjected to a specified test speed of 2 mm/min. Tensile testing with acrylonitrile butadiene styrene was also performed in line with the ASTM D638 standard. It is accomplished by applying a tensile force to a dog-bone specimen and observing the specimen's various properties under stress. The specimen is tensile tested at a rate of 2 mm/min until it fails.The mechanical properties of materials are shown in Table 4 and 5.

Young's Modulus (Pa)	Poisson 's Ratio	Yield Strength (Pa)	Ultimate Strength (Pa)
2.39E+09	0.399	4.14E+07	4.43E+07

Table 4: The tensile properties of ABS.

Property	Value	Unit
Elastic modulus in fibre direction	56.3	GPa
Elastic modulus in transverse direction	8.81	GPa
Shear modulus in 1-2 plane	7.15	GPa
Poisson's ratio	0.20	

Table 5: The tensile properties of U-CFRP.

3.6 Three Point Bending Test

The bending test uses the electronic universal testing machine. The type is Shimadzu Autograph AG-IS 100 KN with a maximum loading force of 100 KN. The loading program corresponds to the American Society for Testing and Materials which are ASTM C393 standard test technique for flexural characteristics of sandwich structures. The test principle is to evaluate the force-deflection of the sandwich construction using the beam three-point bending test. The bending specimen is placed in the middle of the upper indenter and the below supports, which are both steel cylinders. A 150 mm support span with the centre loading is used in the three-point flexure test. The diameter of the indenter and the support were 25 mm. After the specimen has been secured, the universal testing machine's zero point is adjusted, and the load is delivered vertically to the centre of the specimen. The test indenter's loading rate is 6 mm/min and the sampling rate was every 0.25 seconds. Figure 3 depicts a three-point bending test for sandwich beam. The test is conducted until the maximum load has dropped and the load has stabilised. After the test was done, the bending stiffness and strength can be determined by using the Equation (1) and (3).

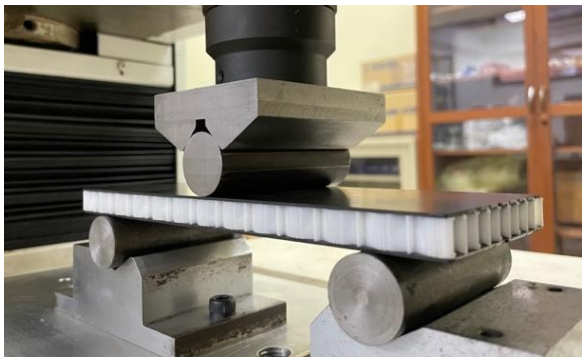


Figure 3: Three-point bending test for sandwich beams with the loading span of 150 mm.

IV. RESULTS

Figure 4 depicts the load-deflection curves of a sandwich beam arrangement with a re-entrant honeycomb core at relative core densities of 0.3 and 0.5. The load-deflection curves can be mainly divided into three main stages. The first stage is the linear elastic stage, the force increases linearly until reaches its peak. The second stage, after the yield point there is an abrupt decrease in load. The final stage is where the load has steadied. The load-deflection curves of a sandwich beam arrangement with a hexagonal honeycomb and circular honeycomb core at relative densities of 0.3 and 0.5 with unidirectional carbon fibre reinforced polymer face sheets are shown in Figures 5 and 6, respectively, these sandwich beams with alternative core topologies display the same response. Load and deflection have been seen to increase significantly with increasing relative density. The subsequent phases demonstrate the same regularity, with a considerable increase in load-bearing capacity as relative density rises, meaning that a core with a high relative density has a greater ability to resist bending forces.

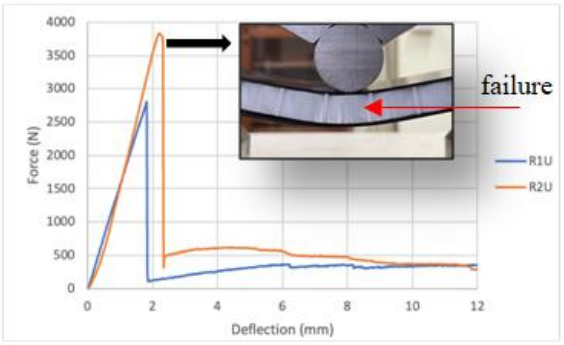


Figure 4: Load-deflection curves of sandwich beam with re-entrant honeycomb core at relative density of 0.3 and 0.5.

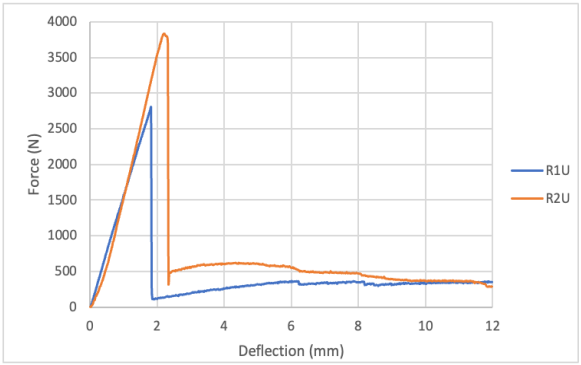


Figure 5: Load-deflection curves of sandwich beam with hexagonal honeycomb core at relative density of 0.3 and 0.5

Sample	Core mass (g)	Core parallel and flat	Sandwich beam thickness (mm)	Beam thickness (Standard Deviation)	Sandwich beam mass (g)
H1U	75.80	Yes	12.68	0.04	97.51
H2U	112.13	Yes	12.78	0.07	123.52
R1U	76.10	Yes	12.39	0.06	97.22
R2U	111.93	Yes	12.56	0.03	125.64
C1U	75.73	Yes	12.81	0.03	103.87
C2U	111.43	No	12.63	0.11	132.36

Core Topology	Core Relative Density	Configuration		
		P_m (N)	σ_s (MPa)	k (N/mm)
Hexagonal	0.3	2281	47.5	1464
	0.5	3142	65.4	1497
Re-entrant	0.3	2800	58.3	1524
	0.5	3840	80	2022
Circular	0.3	2912	60.6	1572
	0.5	3571	74.4	1484

Table 6: Peak load in unit N, bending strength in unit MPa and bending stiffness in unit N/mm obtained for each scenario of sandwich beam with honeycomb core.

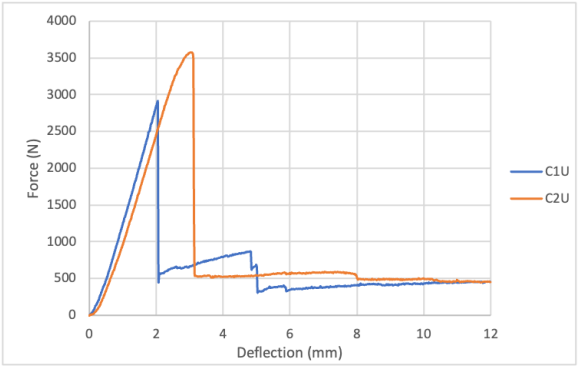


Figure 6: Load-deflection curves of sandwich beam with circular honeycomb core at relative density of 0.3 and 0.5.

V. DISCUSSION

The core structure and relative density of the core were compared in the cases of re-entrant honeycomb, hexagonal honeycomb, and circular honeycomb. Each scenario takes the core density at 0.3 and 0.5 into account. Taking into account the impact of core density on bending strength, as the relative core density increased so did the bending strength increased, as seen in Table 6. By increasing the relative core density from 0.3 to 0.5, the bending strength of both hexagonal and re-entrant honeycomb was raised by about 37%. Moreover, the bending strength of circular honeycomb was raised by about 22%. The greater relative core density indicates that the structure of the cell wall is more densely packed, resulting in an increase in the unit cell's surface area. As the surface area increases, the stress distribution along the sandwich core structure will changed. Additionally, the maximum stress will be reduced when the relative core density increased. This behaviour gives the structure a greater ability to withstand greater loads. Therefore, in order to design the strength of the sandwich panel, a higher relative core density can resist a larger bending strength.

In addition, take into account the influence of core topology on bending strength. For all three fundamental honeycomb topologies, including hexagonal, re-entrant, and circular. The hexagonal honeycomb has the lowest bending strength of all relative core densities, as is evident. While the re-entrant has the highest bending strength value followed by the circular honeycomb. This is because the re-entrant structure has a negative Poisson's ratio.

As a result of negative Poisson's ratio, structures shifted closer together, allowing them to withstand more bending resistance. This characteristic enables the re-entrant structure to withstand greater bending loads. During bending deformation, the hexagonal and circular structures behave differently than the re-entrant structure, suggesting a positive Poisson's ratio.

Consider also the impact of core density on bending stiffness. The bending stiffness of re-entrant was enhanced by 32%, while the bending stiffness of hexagonal was increased by 2.2%. This implies that the structure with negative Poisson's ratio and larger relative core density can resist more bending stiffness. In contrast, the bending stiffness of the circular at a relative density of 0.5 was reduced by 5% compared to its bending stiffness at a relative density of 0.3. According to Equation (2), the bending stiffness of a material with a higher relative density should be greater than that of a material with a lower relative density because the relative core density increases, the elastic core modulus also increases. However, this peculiar behaviour of bending stiffness for circular honeycomb at relative density of 0.5 might be the error of the specimen's manufacturing procedure. The circular sandwich beam with a relative density of 0.5 was not properly bonded between the face sheet and the core, as shown by the thickness standard deviation value in Table 3. This indicates that the bending stiffness of circular sandwich honeycomb with a relative density of 0.5 was unacceptable. Additionally, an excessive amount of epoxy was used to produce the circular sandwich honeycomb, which was heavier than other samples. This higher amount of epoxy allows the structure to withstand the increased bending load, resulting in an increase in bending stiffness.

To compared the effect of core topologies on bending stiffness, the moment of inertia of the re-entrant and circular structures was greater than that of the hexagonal structure. As a result, it can be seen that the bending stiffness of the circular honeycomb topology and the re-entrant honeycomb topology tend to have significant similarities and higher than hexagonal topology.

VI. CONCLUSIONS

We have produced a unique class of sandwich composite structures using 3D-printed core materials consisting of Acrylonitrile Butadiene Styrene and carbon fibre reinforced polymer face sheets. At core densities of 0.3 and 0.5, hexagonal honeycomb, re-entrant honeycomb, and circular honeycomb are proposed as core topologies. On these sandwich composite constructions, bending strength and bending stiffness are evaluated via three-point bending tests. The sandwich composite beam with the greater relative core density displays greater bending strength and stiffness than the sandwich composite beam with the lesser relative core density. The re-entrant and circular honeycomb core designs have superior bending strength and stiffness compared to the hexagonal honeycomb core design. The relative core density and core topologies especially core with negative Poisson's ratio affect the bending strength and stiffness of the sandwich beam, as is evident. These results provide fresh light on the design of sandwich composite structures with exceptional mechanical characteristics for a broad variety of industrial and structural applications.

Increasingly, aeroplanes, ships, and other specialised vehicles are considering sandwich composites for use as structural components, as well. Static and dynamic loads are often applied to sandwich composites. As a result, we conduct a three-point bending test to determine how the material bends. More materials, geometric and topological architectures of the core should be studied in the future to combine the deformation of continuous phases to attain greater bending performance.

REFERENCES

[1] H.Y. Sarvestani, A.H. Akbarzadeh, A. Mirbolghasemi, K. Hermenean, "3D printed meta-sandwich structures: failure mech-anism, energy absorption and multi-hit capability" Mater Des, vol. 160, pp. 179-193, 2018.

[2] W. Hao, J. Xie, F. Wang, "Theoretical prediction for large deflection with local indentation of sandwich beam under quasi-static lateral loading"Compos Struct, vol. 192, pp. 206-216, 2018.

[3] M. Sun, D. Wowk, C. Mechefske, I.Y. Kim, "An analytical study of the plasticity of sandwich honeycomb panels subjected to low-velocity impact"Compos B Eng, vol. 168, pp. 121-128, 2019.

[4] Bandyopadhyay, S. Vahabzadeh, A. Shivaram, S. Bose, "Three-dimensional printing of biomaterials and soft materials" MRS Bull, vol. 40, pp. 1162-1169, 2015.

[5] L.G. Blok, M.L. Longana, H. Yu, B.K.S. Woods, "An investigation into 3D printing of fibre reinforced thermoplastic composites"AdditManuf, vol. 22, pp. 176-186, 2018.

[6] K. Morioka, Y. Tomita, "Effect of lay-up sequences on mechanical properties and fracture behavior of CFRP laminate composites"Mater Charact, vol. 45, pp. 125-136, 2000.

[7] J.V. Campen, C. Kassapoglou, Z. Gurdal, "Generating realistic laminate fiber angle distributions for optimal variable stiffness laminates"Compos B Eng, vol. 43, pp. 354-360, 2012.

[8] M.B. Whiteside, S. Pinho, P. Robinson, "Stochastic failure modelling of unidirectional composite ply failure"ReliabEng Syst Saf, vol. 108, pp. 1-9, 2012.

[9] R.S. Lakes, K. Elms, "Indentability of conventional and negative Poisson's ratio foams"J Compos Mater, vol. 27, pp. 1193-1202, 1993.

[10] L.J. Gibson, M.F. Asbhy, Cellular Solid: Structure and Properties, 2nd ed.; Cambridge: Cambridge University Press, United Kingdom, 1997.

[11] T. Li, Y. Chen, X. Hu, Y. Li, L. Wang, "Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties"Mater Des, vol. 13, pp. 247-258, 2018.

[12] Z. Li, J. Ma, "Experimental study on mechanical properties of the sandwich composite structure reinforced by basalt fiber and nomex honeycomb"Mater, vol 13, pp.1870, 2020.

[13] X. Gao, M, Zhang, Y. Huang, L. Sang, W. Hou, "Experimental and numerical investigation of thermoplastic honeycomb sandwich structures under bending load"Thin-Walled Struct, vol. 155, pp.106961, 2020.

[14] C.A. Steeves, "Optimizing sandwich beams for strength and stiffness"J Sandw Struct Mater, vol. 14, pp. 573-595, 2012.
[15] H. Fukuda, G. Itohiva, A. Kataoka, S. Tashiro, "Evaluation of bending rigidity of CFRP skin-foamed core sandwich beams"J Sandw Struct Mater, vol. 6, pp. 75-92, 2004.
[16] Khurram, M.A. Razza, P. Zhou, T. Subbani, "A study of the nanocomposite sandwich structures for broadband microwave absorption and flexural strength"J Sandw Struct Mater, vol. 6, pp. 739-753, 2016.
[17] Z. Li, L. Wang, "Bending behavior of sandwich composite structures with tunable 3D-printed core materials"Compos Struct, vol. 175, pp. 46-57, 2017.
[18] T.C. Lin, T.J. Chen, J.S. Huang, "In-plane elastic constants and strengths of circular cell honeycombs" Compos Sci Technol, vol. 72, pp. 1380-1386, 2012.

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