Engineering Journal
issn: 0125-8281

*Review*

# A Review of Sandwich Composite Structures with 3D Printed Honeycomb Cores

**Dechawat Wannarong**[a] **and Thanyarat Singhanart**[b,*]

Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
E-mail: [a]dechawatwannarong@gmail.com, [b,*]Thanyarat.S@chula.ac.th (Corresponding author)

**Abstract.** Sandwich structures have picked up ubiquity in engineering applications due to its lightweight nature, high bending stiffness, high fatigue resistance and ability to absorb energy. It is difficult to retain the lightweight execution of a sandwich construction whereas moreover getting great bending stiffness and strength. The mechanical characteristics of Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) produced via additive manufacturing are investigated in this article. The most often used materials for cores are ABS and PLA. ABS appears to have more flexural strength and elongation before failure than PLA. The behaviour of cores is also examined. The bending stiffness was discovered to be enhanced by the re-entrant core which is the core that exhibits negative Poisson's ratio or auxetic behaviour. The bending and fatigue performance of sandwich structures is controlled by the core densities, core designs, component materials, face sheet thickness, and face sheet stacking sequence. Furthermore, the findings revealed that finite element analysis may be utilized to investigate the mechanical characteristics of sandwich constructions with honeycomb cores. The discoveries presented here open the path for the development of a new class of sandwich structures, greatly expanding their design space and potential future applications.

**Keywords:** Sandwich beam, honeycomb core, lightweight structure, bending stiffness, fatigue.

**ENGINEERING JOURNAL** Volume 26 Issue 6
Received 21 September 2021
Accepted 5 June 2022
Published 30 June 2022
Online at https://engj.org/
DOI:10.4186/ej.2022.26.6.27

DOI:10.4186/ej.2022.26.6.27

## 1. Introduction

Sandwich composite structures are increasingly being used in variety of engineering applications, including automotive, aerospace, satellite applications, marine vessels and others [1]. A structure usually consists of three substructures. The outermost layer is made up of a thin layer that aims to spread burst pressure more uniformly over the second and third substructure known as bonding layer and core, respectively. Among various structural types, honeycomb architectures have the advantage of enhancing the bending stiffness, as well as enhancing buckling resistance. A large number of experiments have been conducted to uncover the complexity of core's architectures and topologies [2, 3]. The mechanical performance of a sandwich structure is influenced by the materials used in its construction, the core topology and the geometry of the face layer [4]. There are various core topologies that have been studied, including conventional structure, re-entrant structure, truss structure, circular structure and others. The conventional structure is the most commonly used for the core [5].

Additive manufacturing is gaining popularity in both research and industrial applications. There are presently several commercially accessible additive manufacturing methods, with metal technology dominating what is utilized in industry [6]. The most often utilized filaments in 3D printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) [7]. ABS is praised for its toughness, whilst PLA is praised for its pliability. Fibre reinforced polymers have recently shown to be extremely beneficial in the repair, rehabilitation, and strengthening of masonry due to their excellent strength and stiffness to weight ratios, as well as their anti-corrosion properties [8]. The performance of fibre reinforced polymers has received a lot of interest from academics and industry.

Several attempts have been made in the recent decade to conceptualize the behaviour of negative Poisson's ratio materials from the standpoint of microstructure. A relatively new class of honeycombs with auxeticity behaviour and a negative Poisson's ratio have lately piqued the curiosity of researcher due to their unusual feature of becoming thicker when stretched [9]. The mechanical behaviour of a sandwich composite is determined by the material used in its manufacture, the geometry of the face sheets, and, most importantly, the core topology [5]. The bending behaviour of sandwich composites is investigated, pointing to its potential in structural applications. Furthermore, the geometric configuration, material kinds, and loading arrangement all influence the failure behaviour of sandwich structures. As a result, each type of sandwich structure's failure process must be investigated. To employ these materials in diverse applications, knowledge of their static and fatigue behaviour is essential, as is a better understanding of the various failure process under static and fatigue loading circumstances [10].

Numerous studies have been conducted in order to get a better understanding of the mechanical characteristics of sandwich composite constructions. This includes the degree of complexity associated with core deigns and topologies. Difficult service circumstances are becoming more widespread, resulting in a broader range of damage threats when subjected to a variety of pressures, including axial compression, localized impact, and bending. Sandwich structure's strength and stiffness must be investigated when exposed to bending stresses. As a consequence, this article synthesises the mechanical characteristics of a sandwich composite construction with a honeycomb core in a systematic manner. This research also looked at the various materials used, the core topologies, core textures, core densities, and face sheet thickness. The mechanical behaviour of 3D printed based materials and fibre-reinforced polymers are reviewed in section 2. The negative Poisson's ratio, the bending behaviour of sandwich panels, and fatigue behaviour of sandwich panels are reviewed in section 3, 4 and 5, respectively.

## 2. Mechanical Behaviour of 3D Printed Based Materials and Fibre-Reinforced Polymers

Additive manufacturing is gaining popularity for both research and industrial uses. The term added substance alludes to the way that as opposed to eliminating material to frame a segment as is done in conventional methodology. The capacity to realize components and products with high levels of intricacy in combinations that would otherwise be impossible was one of the benefits of 3D printing [11]. The most often utilized filaments in 3D printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). Saad and Sabah investigated the mechanical characteristics of ABS and PLA created using fused deposition modelling, a form of additive manufacturing process. The design comprises a core design that increments the infill parentage by expanding the volume of hexagonal pores. Tensile strength and modulus were found to rise significantly as packing density increased. This rise in tensile strength and modulus is caused by an increase in the number of honeycomb cores and as the cross-sectional area increases this leads to greater resistance to applied forces [12]. Compared to other thermoplastics, ABS has a higher resistance to bending and elongation before breaking. PLA is praised for its flexibility, while ABS is praised for its toughness [13]. Furthermore, the flexural and tensile properties of blended materials as well as traditional ABS and PLA were evaluated using ASTM D638 for tensile testing and ASTM D790-17 for flexural testing. The printing parameters of the samples were carried out at various feed-rates. According to the findings, specimens made out of 80% PLA and 20% ABS had stronger tensile strength than other specimens. Although the samples generated at lower feed rates proved to be superior because the structure of the polymer microfibres was clearer and more consistent, the overall strength was improved. However, when 100% ABS and 100% PLA are considered. ABS outperformed PLA in terms of flexural strength and elongation before breaking. ABS, on the other hand, has a lower tensile strength than PLA, as demonstrated in Table 1 and 2 [7]. This discovery is consistent with the trends documented by Blok et al. [13] for conventional materials.

Table 1. Tensile test results [7].

| Specimen label | Maximum load $(kN)$ | Breaking load $(kN)$ | Loading at strain (8%) $(kN)$ | UTS $(MPa)$ |
|---|---|---|---|---|
| ABS | 0.68 | 0.42 | 0.42 | 13.46 |
| PLA | 1.03 | 0.96 | 0.73 | 20.35 |
| 20%ABS, 80%PLA | 1.18 | 1.07 | 0.83 | 21.40 |
| 80%ABS, 20%PLA | 0.65 | 0.44 | 0.43 | 13.20 |

Table 2. Flexural test results [7].

| Specimen label | Maximum load applied $(kN)$ | Maximum stress $(MPa)$ | Strain at maximum stress | Extension at maximum load (mm) |
|---|---|---|---|---|
| ABS | 34.89637 | 19.24 | 0.0556 | 8.87586 |
| PLA | 32.16785 | 17.90 | 0.06402 | 4.62973 |
| 20%ABS, 80%PLA | 31.6251 | 16.23 | 0.06493 | 6.74632 |
| 80%ABS, 20%PLA | 33.68724 | 18.03 | 0.04752 | 8.9879 |

Furthermore, the layer thickness and cross section shape have an impact on the mechanical properties of 3D printed materials. The research from Wang, Lin, and Hu discovered that ABS printed with a thickness layer of 0.254 mm had greater tensile strength than samples printed with a thickness layer of 0.330 mm [14]. These findings are consistent with the findings of Tymrak, Kreiger, and Pearce who investigated the tensile strength ABS and PLA at various deposition layer thickness. The results showed that samples with thinner layer thicknesses had better tensile strength than those with bigger layer thicknesses [15]. However, there are some differences between their research and those of Sood, Ohdar, and Mahapatra, who investigated the tensile strength of ABS printed materials as well. ABS was printed with layer thicknesses ranging from 0.127 to 0.254 mm. The study discovered that bigger layer thicknesses had better tensile strength than smaller layer thicknesses because to poor interlayer bond strength and deformation [16]. Nomani et al. investigated the mechanical characteristics of 3D printed ABS in their study. It was discovered that samples with the minimum evaluated layer thickness of 0.2 mm had the best strength qualities. The greatest studied layer thickness of 0.8 mm, on the other hand, recorded the worst strength qualities [17].

The sample porosity, printing orientation, number of deposited layers, and strain hardening all had an influence on material strength. When printing with a thicker layer, the porosity of 3D printed materials was shown to be increased, resulting in inferior strength properties. It was discovered that as the number of layers present in a fixed volume rose, so did the total sample strength [17]. Fibre-reinforced polymers (FRP) has proved to be favorable in terms of high strength, stiffness to weight ratio, and corrosion resistance. The primary choice for rehabilitating and reinforcing old structures is fibre-reinforced polymers [18]. Glass fibre-reinforced polymers (GFRP) and carbon fibre-reinforced polymers (CFRP) are two examples of fibre-reinforced polymers. The performance of FRP at higher temperatures has piqued the interest of industry and academics. The mechanical characteristics of FRP bars at elevated temperatures were reported by Hamad, Megat Johari, and Haddad. The results showed that at the critical temperature of 325℃, their elastic modulus and tensile strength were reduced roughly 30% and 55%, respectively [19]. The mechanical characteristics of FRP below the glass transition temperature were discovered to have no significant losses in strength and stiffness. When FRP composites approach the glass transition temperature, resulting in a considerable loss of stiffness and strength due to the resin transitions from a glassy to a rubbery condition [8].

## 3. Negative Poisson's Ratio

Materials with a negative Poisson's ratio, also known as auxetic materials, are a novel class of mechanical metamaterials with the unusual feature of becoming thicker when expanded [9]. The geometric format of the unit cell and the mechanical characteristics of the core fabric may characterize the straight elastic behaviour of common honeycombs [20]. Many research has been conducted to study the influence of a negative Poisson's ratio on the mechanical characteristics of honeycomb cores. Li et al. [21] examined the mechanical characteristics of honeycomb cores with a negative Poisson's ratio, including a chiral truss and re-entrant honeycomb, as illustrated in Fig. 1(a) and Fig. 1(b). These cores are compared to the non-negative Poisson's ratio, which included a honeycomb and a truss, as illustrated in Fig. 1(c) and Fig. 1(d). The specimens are created using a 3D printer with 4x4 unit cells for each specimen. The results show that auxetic lattice reinforced composites outperform non-auxetic lattice reinforced composites in terms of mechanical performance, offering a unique combination of energy absorption and stiffness [21].

(a)

DOI:10.4186/ej.2022.26.6.27


(d)

Fig. 1. Diagram of cores geometry made up of 4x4 unit cells with: (a) chiral truss; (b) re-entrant honeycomb; (c) honeycomb; (d) truss [21].

Miller et al. [22], on the other hand, studied the mechanical behaviour of a honeycomb core with chiral structure. The rests were delivered utilizing particular laser sintering of Nylon powder. The findings demonstrated that the structures had a negative Poisson's ratio, which is consistent with the findings of Li et al. [21]. These finding corroborated the findings of Scarpa and Tomlinson [23], who explored the mechanical characteristics of auxetic honeycombs. The results revel that the re-entrant honeycomb core has in-plane negative Poisson's ratio behaviour. Auxetic materials with a negative Poisson's ratio have been proved to have higher bending stiffness, higher buckling stresses, and lower modal densities. The volume fraction has an effect on the mechanical characteristics of materials. As seen in Fig. 2(a) and Fig. 2(b), as the volume fraction increases, so do the overall mechanical properties. The stress-strain bends experience a move from rubber-lime hyperelastic behaviour to a profoundly nonlinear behaviour, which is taken after by fragile break [21].

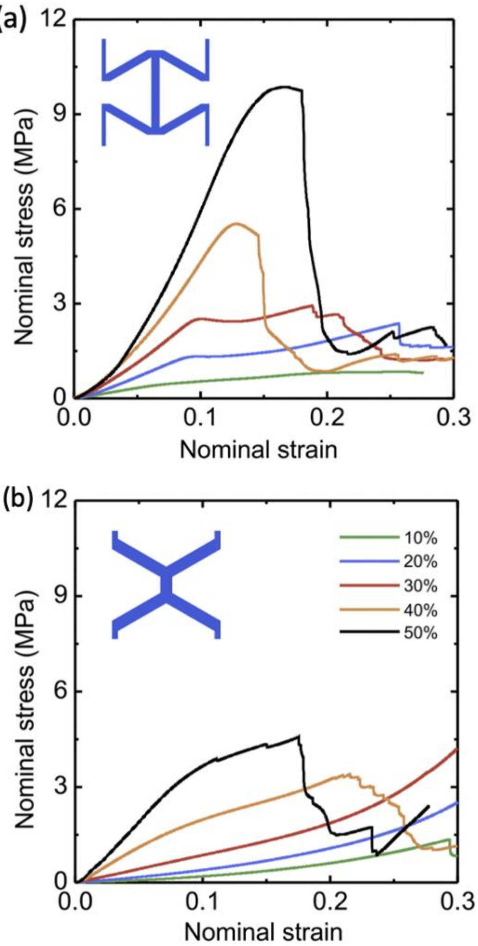


Fig. 2. At varying volume fraction, the stress-strain response: (a) re-entrant honeycomb; (b) honeycomb [21].

## 4. Bending Behaviour of Sandwich Panels

Sandwich structures, due to their high bending stiffness and energy absorption capabilities, are currently widely used as low weight components in aircraft, car, and civil engineering industries [24]. A structure usually consists of three substructures. The outer most layer is made up of a thin layer that aims to spread burst pressure more uniformly over the second and third substructure known as bonding layer core, respectively, as shown in Fig. 3. A number of studies have shown that component material, geometrical factors, and core cell architecture all have a significant impact on mechanical performance, both experimentally and theoretically [25, 26]. Sandwich constructions were frequently subjected to three-point bending loads in engineering applications. As a result, in actual applications, the examinations of bending performance, including failure load, stiffness and failure causes, is a key problem [27]. With the growing need for lightweight and performance-based materials in the structural area, new composite materials like as foam, fibre and honeycomb have seen increased application. Glass, carbon, aramid, and basalt fibres are examples of representative fibres. Aramid, aluminium honeycomb, and other materials are used to make honeycomb. Basalt fibre has steadily risen to prominence among these high-tech fibres in recent years due to its low cost and environmental

DOI:10.4186/ej.2022.26.6.27

friendliness. Li and Ma investigated the bending behaviour of a sandwich composite structure reinforced with basalt fibre and nomex honeycomb [28].

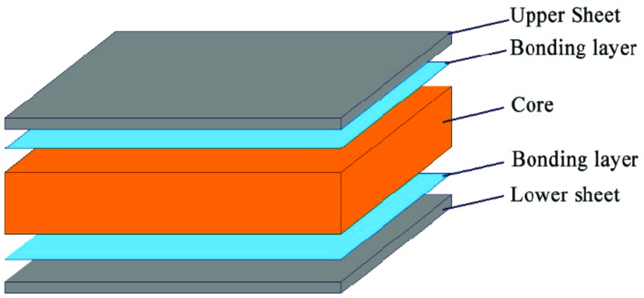


Fig. 3. The formation of the sandwich structure [28].

Figure 4. depicts the topology of a honeycomb sandwich panel. In order to evaluate the bending performance, the samples are made with varying sheet thickness and core height. Bending tests are carried out using a span length of 120 mm. The results show that the internal core effectively separates the top and bottom sheets, thereby increasing the moment of inertia of the frame section, which subsequently has a significant impact on the flexure characteristics of the sandwich panel. The three-point bending test was used to determine the failure mechanism of the sandwich panels and factors influencing its flexure characteristics. Li and Ma has called out the bending procedure of the basalt fibre-Nomex honeycomb construction is divided into five steps as shown in Fig. 5. The first stage is called elastic stage is the stage is when there is no visible distortion of the honeycomb. The second stage, known as the yielding stage, occurs when the displacements rise while the load decreases significantly. The honeycomb's height and form stay constant. The third stage was the stacking stage. The honeycomb walls were found to be folded. The core layer and the sheet may be degummed at this point, resulting in a rapid reduction in force. The sheet resistance stage comes next. The honeycomb was folded into a spring form at this point, and the honeycomb simply served as a connecting sheet. The final step is the sheet broken stage. The force fell abruptly and steadily as the displacement increased. Finally, the basalt fibre sheets and honeycomb were largely out of work, but due to the intact resin and the fibre sheets, the specimens could still discharge after unloading.

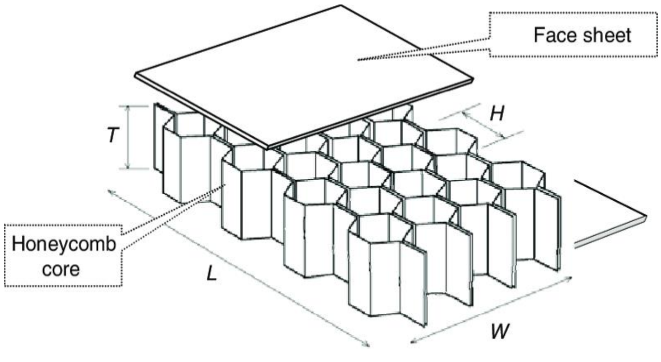


Fig. 4. Shape of the honeycomb [29].

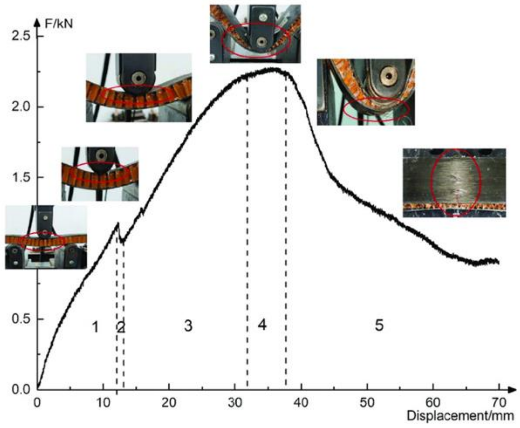


Fig. 5. Failure mode of bending samples [28].

Furthermore, by increasing the thickness of fibre sheets in specimens with the same direction and height, the shear stress of the core may be efficiently enhanced. The higher the honeycomb in the same direction and with the same thickness of fibre sheet, the lower the shear stress of the honeycomb core. According to previous research, the primary parameters influencing flexure characteristics are sheet thickness, honeycomb height, and honeycomb orientation [28].

Sandwich cores are best made with Nomex paper honeycombs. These lightweight cores have low compressive and shear characteristics, resulting in significant deflection. However, these sandwich constructions are often made of traditional thermoset or metallic mixed incompatible materials, which creates a recycling issue. To address this issue, recyclable thermoplastic materials are becoming increasingly popular in current engineering applications. Gao et al. [30] created completely thermoplastic honeycomb sandwich structures out of continuous glass fibre-reinforced polypropylene face sheets, polypropylene core and assembled using thermoplastic films. Figure 6. shows the structure of the sandwich panels which have a hexagonal core which were used for the static three-point bending tests. A combination of experimental results and finite element analysis was employed to explore the bending performance, as indicated in Fig. 7. The three-point bending tests were performed with the goal of maximizing the energy absorption through the principal factors such as height and diameter of the honeycomb core, and the ply sequence, and thickness of the face sheets. The samples used were produced with designs which varied the specific parameters to be tested.

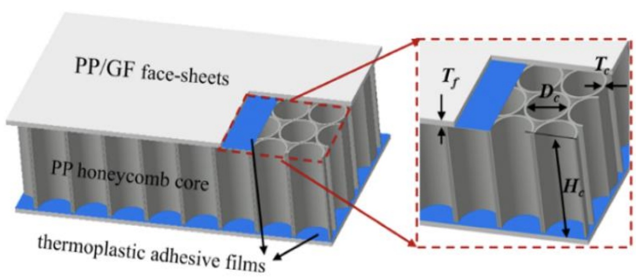


Fig. 6. Structure diagram showing the PP-based sandwich structures [30].

DOI:10.4186/ej.2022.26.6.27

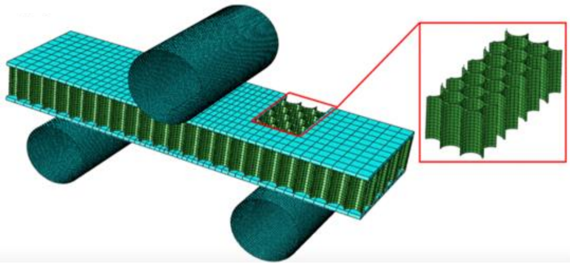

Fig. 7. The finite element model to perform the three-point bending test with sandwich beams [30].

The experimental findings allowed determination of the mean crushing force ($F_{avg}$), peak force ($F_{max}$), energy absorption ($E_a$) and specific energy absorption ($SEA$). The load displacement curve allowed calculation of the peak force, which typically arose at the conclusion of the elastic displacement, which was directly associated with the crushing strength. Energy absorption is defined as the energy absorbed by the sandwich structure through a particular specific crushing distance $d$ from the midpoint deflection, which can be calculated as:

$$E_a = \int_0^d F(\delta)d\delta \quad (1)$$

in which $F(\delta)$ was the force instantaneously deployed at displacement.

To acquire the mean crushing force ($F_{avg}$), energy absorption can be divided by the crushing distance, using the equations given as:

$$F_{avg} = \frac{E_a}{d} = \frac{1}{d}\int_0^d F(\delta)d\delta \quad (2)$$

The sandwich structure, which has mass $m$, exhibits an energy absorption efficiency which can be expressed in terms of the specific energy absorption derived from:

$$SEA = \frac{E_a}{m} = \frac{\int_0^d F(\delta)d\delta}{m} \quad (3)$$

in which $m$ represents the structural mass of the body absorbing the energy. Table 3 shows the findings from the experimental three-point bending test in which term P(number) was indicative of the particular stack sequence: P1 for 0°/0°/0°/0°, P2 for 0°/90°/0°/90°, P3 for 45°/-45°/45°/-45°, P4 for 0°/45°/90°/-45°, and P5 for 90°/90°/90°/90°. The face sheet thickness was represented by the term F(number), while the honeycomb core height was given by H(number) and the core thickness by D(number). A slight difference was observed between the experimental results and the findings from the finite element analysis yield. The structural parameters of the tested sandwich structures had a notable influence upon the peak force and specific energy absorption. Meanwhile, the ply sequence and the face sheet thickness had the greatest effect upon the failure modes, in concurrence with Li and Ma [28, 30].

Some studies have argued that the sandwich beam bending qualities are affected by the core topologies. It can be very difficult to construct a lightweight sandwich structure which simultaneously offers great strength as well as a high degree of bending stiffness. The hierarchical honeycomb mixes the notion of hierarchy with a thin-walled honeycomb structure. It has since been shown that the component of hierarchy serves to improve the overall mechanical performance. Li et al. [31] conducted a study of the bending properties of tailored hierarchical honeycomb cores. The hierarchical sandwich beam proposed in this study was created using a hierarchical honeycomb core in which smaller honeycomb cells replace the vertices of the original honeycomb. In Fig. 8(a), a representative hierarchical sandwich beam featuring a partial visible core is presented. Meanwhile, Fig. 8(b) presents the details of the vertex-based hierarchy, while Fig. 8(c) shows the honeycomb core thickness and the thickness of each face sheet, respectively indicated as $C_1$ and $C_2$. Sandwich structures have mechanical properties which are primarily dependent upon the materials involved as well as the geometry of both the surface and the core. To better understand the attributes of the hierarchical sandwich beam in terms of bending, a study of equivalent bending stiffness (indicated as $D$) was performed. This particular criterion is a useful indicator of the likely capacity for bending resistance. The analytical approach used here shows the elastic analysis. It can be postulated that there remains a firm bond between the skins and the honeycomb core, whereupon bending behaviour takes place in the YZ plane while the sandwich beam shear compliance can be ignored [32, 33].

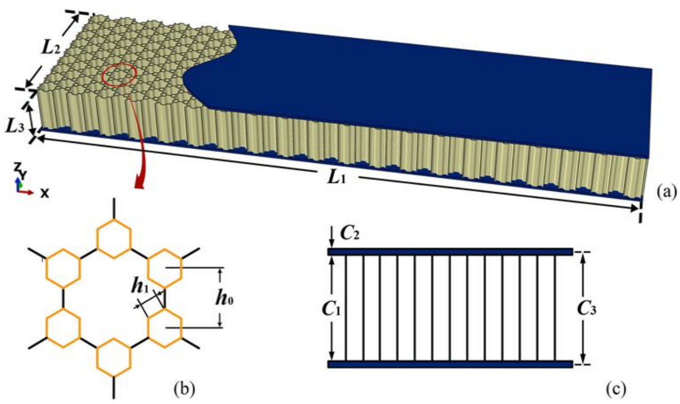


Fig. 8. Geometric illustration of a sandwich beam featuring a hierarchical honeycomb core: (a) a representative hierarchical sandwich beam featuring a partial visible core; (b) a representative honeycomb cell from the proposed core which has the same length as the original cell, $h_0$, and vertex cell, $h_1$; (c) a side view of the sandwich beam indicating the relevant geometric parameters [31].

Table 3. Peak force, energy absorption, mean crushing force and specific energy absorption of sandwich beams with varying parameters under three-point bending tests [30].

| Sandwich | Parameter | Specimen | $F_{max}$(N) | $E_a$(J) | $F_{avg}$(N) | SEA (J/g) | Mode |
|---|---|---|---|---|---|---|---|
| Face-sheet | Stack sequence | P1-F1.0-H20-D8 | 1938.89 | 41.81 | 1393.66 | 0.69 | Half-elliptic |
| | | P2-F1.0-H20-D8 | 1543.19 | 35.74 | 1191.35 | 0.59 | V |
| | | P3-F1.0-H20-D8 | 1267.41 | 27.44 | 914.78 | 0.46 | Half-elliptic |
| | | P4-F1.0-H20-D8 | 1418.35 | 28.88 | 962.73 | 0.48 | Half-elliptic |
| | | P5-F1.0-H20-D8 | 643.22 | 3.66 | 122.15 | 0.06 | - |
| | Thickness | P2-F1.5-H20-D8 | 1993.19 | 37.48 | 1249.27 | 0.44 | Half-elliptic |
| | | P2-F2.0-H20-D8 | 2195.16 | 39.91 | 1330.21 | 0.36 | Half-elliptic |
| Honeycomb core | Height | P2-F1.0-H10-D8 | 1123.68 | 17.69 | 589.51 | 0.32 | V |
| | | P2-F1.0-H15-D8 | 1269.71 | 20.41 | 680.36 | 0.35 | V |
| | Diameter | P2-F1.0-H20-D10 | 1395.19 | 29.32 | 877.42 | 0.50 | V |
| | | P2-F1.0-H20-D12 | 1049.06 | 20.06 | 668.65 | 0.35 | V |

On the basis of typical beam theory, the bending stiffness comprises two components. The first of these concerns the face sheets, whose contribution can be determined by considering the centroid of skins and the sandwich beam as a whole, indicated as $D_1$. A second contribution is made by the sandwich core, designated as $D_2$. It is therefore possible to obtain $D$ via the following:

$$D = D_1 + D_2 = \frac{E_f L_2 C_2{}^3}{6} + \frac{E_f L_2 C_2 C_3{}^2}{2} + \frac{E_c L_2 C_1{}^3}{12} \qquad (4)$$

in which $E_f$ represents the face sheet elastic modulus and $E_c$ represents the sandwich core elastic modulus.

It is important to be able to assess the bending strength and behaviour of sandwich beams since this has a direct influence upon the useful lifespan of the beam. Bending strength is represented by the symbol $\sigma_s$, and is an important component of the overall bending response in the context of sandwich structures. The calculations are carried out on the basis of a simple model of the beam. The structural geometry and statics are taken into consideration along with the inertia moment of the rectangular section, to determine $\sigma_s$ as shown below:

$$\sigma_s = \frac{3P_m L_s}{2L_2 L_3{}^2} \qquad (5)$$

in which $P_m$ is used to show the maximum load, and $L_s$ refers to the distance of the span when conducting the three-point bending test [31].

The work of Li et al. [31] examined bending performance via the finite element tool by testing sandwich beams. The findings related to bending confirmed the superiority of performance for the proposed hierarchical sandwiches when compared to the conventional alternative, revealing greater load-bearing capabilities. When subjected to the same weight, the hierarchical and conventional honeycombs provide similar bending stiffness, while the effect of cell size is relatively important in the context of bending performance. For the typical hierarchical design, significantly greater load bearing is achieved by smaller cell sizes, while the use of squares and circles in the patterns of the sandwich core serves to support bending resistance. Sandwich beams for which the design is typical hierarchical, circular, or square, are able to match the bending resistance capabilities of conventional sandwich designs. In the case of the square pattern, which has larger square cells, there is however a decline in the stability of the loading process.

The finite element model underwent validation by performing three-point bending tests using conventional honeycomb sandwich panels. Under the two methods, it was apparent that the deformation behaviours were very similar, and exhibited the same local indentation patterns. The high degree of agreement provides adequate validation of the finite element model, and the consistency confirms the suitability of the finite element model as a tool to examine the behaviour of the sandwich structure under three-point bending conditions [30, 31]. Therefore, the finite element model can be considered as an acceptable approach whenever the honeycomb core design of a sandwich beam must be simulated.

The mechanical qualities of any sandwich structure will be affected by the material type, the face sheet geometry, and also the core topology design. One core material of note which has been studied is foam, despite the poor scaling which results from the architecture which tends to be dominated by bending [34]. A study of sandwich composite bending properties when the composites comprised three designed core material was performed by Li and Wang [4]. The designs included truss structure, conventional structure, and re-entrant structure, while two different face sheet types were chosen: woven carbon fibre reinforced polymer and unidirectional carbon fibre reinforced polymer. The three designs, conventional honeycomb, and re-entrant honeycomb are then described in detail and explained further. For the truss structure, the relative density can be derived as follows:

$$\frac{\rho^*}{\rho_s} = \frac{t}{L\sin\theta\cos\theta} \qquad (6)$$

While the relative density in the case of the conventional and re-entrant honeycombs can be determined through:

$$\frac{\rho^*}{\rho_s} = \frac{t/L(H/L+2)}{2\cos\theta(H/L+\sin\theta)} \quad (7)$$

in which $\rho^*/\rho_s$ indicated the relative density for the honeycomb structure. The schematic diagrams showing the details of the truss honeycomb, conventional honeycomb, and re-entrant honeycomb structures can be seen in Fig. 9. The work previously carried out by Li and Wang examined a number of differing relative densities. In this particular work, the relative densities investigated are 0.2, 0.3, and 0.4. Accordingly, it is possible to calculate the cell wall thickness using Eq. (6) and Eq. (7). The design of the sandwich beams stipulates dimensions of 108 mm x 21 mm x 10 mm, which can be accomplished using 12 x 2 unit cells.

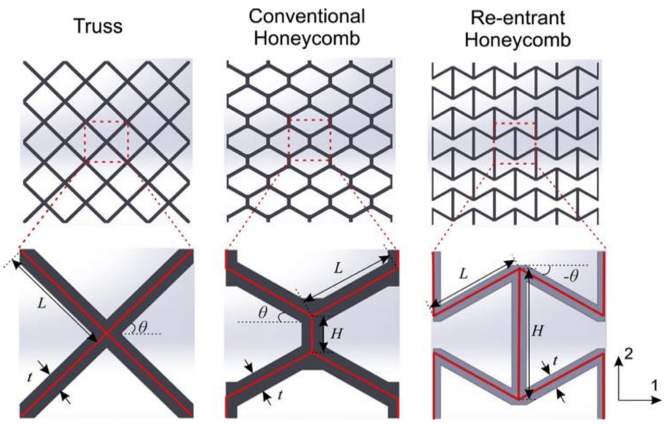


Fig. 9. Unit cell designs for the structures of the truss, conventional honeycomb, and re-entrant honeycomb. $L$ indicates the inclined cell wall length in the truss structures, $t$ indicates the cell wall thickness, and $\theta$ represents the angle between the sloping cell walls. The conventional and re-entrant honeycomb structure shapes can be described in terms of the lengths of the vertical cell walls, $H$; the length of the sloping cell walls, $L$; the cell wall thicknesses, $t$, and the angle between vertical and sloping cell walls, $\theta$ [4].

The material used for the face sheets will significantly influence the bending behaviour. A sandwich sample using VeroWhite face sheets had of load-deflection relationship indicative of the lowest force level due to the greater softness and weakness of VeroWhite in comparison to carbon fibre reinforced polymers. In the case of the sandwich sample constructed using woven carbon fibre reinforced polymer face sheets, there was a significant increase in the load up to the yield point at around 190 N. For the analysis of unidirectional carbon fibre reinforced polymer face sheets, the greatest force level according to the load-deflection curve was seen at around 500 N as presented in Fig. 10(a). It can therefore be seen that unidirectional carbon fibre reinforced polymer is able to significantly improve the energy absorption behaviour of sandwich composites in comparison to the performance of woven carbon fibre reinforced polymer. The varied mechanical responses are inherently linked to the strength and stiffness properties of the face sheets involved. There is also an effect exerted upon bending behaviour by the core topology, and this can be examined numerically and via experimentation. The specific core topology is understood to significantly affect the load-deflection curves, which can be observed in Fig. 10(b). The greatest flexural stiffness and highest loading forces were observed for the truss core sandwich composite, whereas in the case of the re-entrant honeycomb core sandwich composite, the flexural stiffness was the lowest reported and the bending deflection the greatest. This can readily be explained by the fact that the re-entrant honeycomb structure has a significantly reduced Young's modulus and stress level when considered at the same deformation level [4]. These findings were in concurrence with those of Sun et al. [26], Hao, Xie and Wang [25], and Gao et al. [30], who reported that the bending performance is significantly impacted by the material type, geometry, and core cell design and structure, both in theory and under experimental conditions.

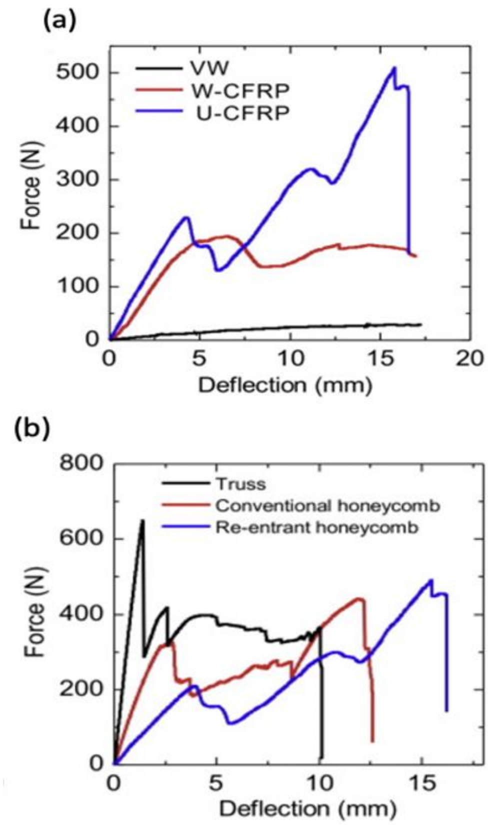


Fig. 10. (a) The bending attributes for sandwich composite samples with face sheets comprising various materials; (b) sandwich composite bending characteristics using various core structures featuring unidirectional carbon fibre-reinforced polymer face sheets [4].

## 5. Sandwich Panel Fatigue Behaviour

Hoenycomb sandwich structures are now in widespread use for many applications as a consequence of the advantages they offer in terms of thermal resistance and bending stiffness. Such sandwich structures may fail, but their failure behaviour will be affected by various factors including materials used, loading configurations, and the geometric arrangements used [35, 36]. Where composite materials are employed, vibration can lead to low-cycle fatigue problems. In planes, it has been reported that around 80% of fractures are a consequence of failure due to fatigue, so the study of this phenomenon to develop a better understanding would appear to be a priority. In particular, the mechanisms by which failures arise in different sandwich structure types must be assessed. Numerous studies have been conducted to date which evaluate honeycomb sandwich structures in terms of their dynamic mechanical properties [37]. Various mathematical models have been created to examine the static and fatigue responses when honeycomb sandwich panels are stressed, but the coefficients and parameters in such equations are both complex and numerous, leading to difficulties in experimental application. Accordingly, some studies have employed common commercial tools including ABAQUA and ANSYS to examine how sandwich structures behave. Finite element analysis can be applied to establish the fatigue properties and mechanical parameters for honeycomb sandwich structures [38]. Fatigue testing was also conducted by Abbadi et al. [39] in a study of honeycomb behaviour in the presence and absence of artificial weaknesses, determining that such defects did not influence the static response. Fatigue analysis techniques using the finite element method are becoming increasingly popular since computer applications involving the finite element numerical method have advanced.

The core topology of the honeycomb, including re-entrants, exhibit a negative Poisson's ratio and are known as auxetic structures [40]. Among the properties of such auxetic structures are enhanced resistance to shearing and indentation, which leads to their potential application in roles which demand resistance to fatigue [41]. The core topology remains the main parameter influencing the way sandwich composites will behave. The response of sandwich composites with an auxetic core to fatigue was tested by Essassi et al. [42] using different stress ratios along with four varied core densities. Sandwiches were examined using cyclic loading tests to carry out experimental and analytical analysis to find out how the stress ratio will affect the response to fatigue. The same materials were used in the construction of all the sandwich structures tested: polylactic acid tape with added flax fibre filaments commonly used in additive manufacturing methods. The auxetic core had a relative density which could be determined using Eq. (7), with measurements taken at 8.3%, 16.7%, 25.1%, and 33.5%. Eq. (8) below defines the loading ratio, $R$:

$$R = \frac{d_{min}}{d_{max}} \tag{8}$$

in which $d_{min}$ and $d_{max}$ represent the respective minimum and maximum displacements which arise in the cycle. Then $d_{mean}$ and $d_{amp}$, the average displacement and amplitude of displacement respectively, were varied as a means of varying the loading level given by $r$ which can be defined as:

$$r = \frac{d_{max}}{d_{rup}} \tag{9}$$

in which $d_{rup}$ indicates the failure displacement level when conducting a quasi-static three-point bending test.

The experiment revealed that sandwiches exhibiting lower relative core densities offered greater resistance to fatigue. Where the core density was relatively high, this would result in failure at a low number of cycles. As the density increases, it is necessary to have a greater quantity of material in the sandwich core, and thus the core becomes more porous, as can be observed in Fig. 11 [42]. In contrast, when the core density is decreased, the flexibility improves and the brittle breakage potential is lowered [4]. The number of cycles required for failure can be evaluated via the Wohler curves, while the maximum levels of stress to be applied to a sandwich beam can be determined by:

$$\sigma_{max} = \frac{F_{max} d}{4bt_f(t_f+t_c)} \tag{10}$$

in which $b$ indicates the beam width and $d$ represents the span length. Maximum stress evolves as a function to failure as follows:

$$\sigma = A - B \ln N_r \tag{11}$$

In this context, $B$ is the parameter which represents the greatest rate of degradation for the material, while the maximum stress applied for low cycle numbers is given by $A$. The longest fatigue life is achieved by those sandwiches which have the lowest core density levels. Furthermore, the highest loads which the sandwich can support will occur in the case of the sandwiches which have lower core densities. It is wholly apparent that core density is an important factor determining sandwich fatigue life, as indicated in Fig. 12 [42].

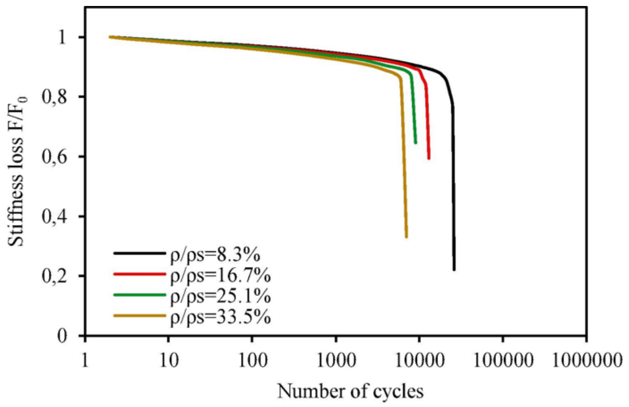


Fig. 11. Stiffness loss versus the number of cycles for a loading level r = 65% of the sandwich composite with different relative core densities [42].

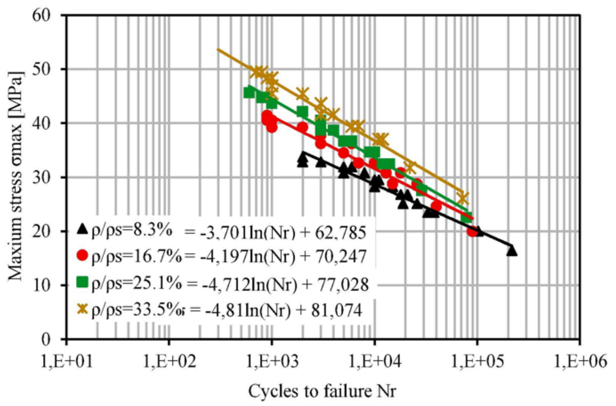


Fig. 12. Wohler S-N diagram comparing the fatigue performance of the sandwich composite with different relative core densities [42].

An analytical and experimental model was formulated by Boukharouba, Bezazi, and Scarpa in order to make predictions of the fatigue life and likely mode of failure for honeycomb sandwich structures when exposed to three-point bending loads. The analysis used coefficients and empirical functions derived from the experimental data and an understanding of the properties of the materials used [43]. An investigation was carried out involving sandwich structures constructed using glass fibre face sheets and a hexagonal honeycomb core made from aluminium in order to assess the bending loads to the point of failure and the life cycle. The finite element method was then used to establish the load-displacement behaviour. The material properties involved were assumed to be elastic plastic. ANSYS was used to conduct the structural analysis by recording the panel fatigue life for each of the different loading levels. The experiments also permitted the determination of the fatigue deflection along the number of cycles while maintaining constant amplitude fatigue loading levels. When fatigue loading is reached, the deflection at mid span shows a constant initial level before suddenly increasing sharply. Minor variations in deflection resulting from face yielding or core-skin interface delamination can be considered as the panel stiffness degradation. Fig. 13 shows the results for the fatigue testing of the panel, allowing comparisons to be drawn between the numerical and experimental findings.

Fatigue testing was performed using various load levels while each cyclic load maintained a constant amplitude. Accordingly, at high loading levels, fatigue failure initiation can be attributed to face yielding. In contrast, at low loading levels it results from interfacial delamination which in turn causes indentation [44].

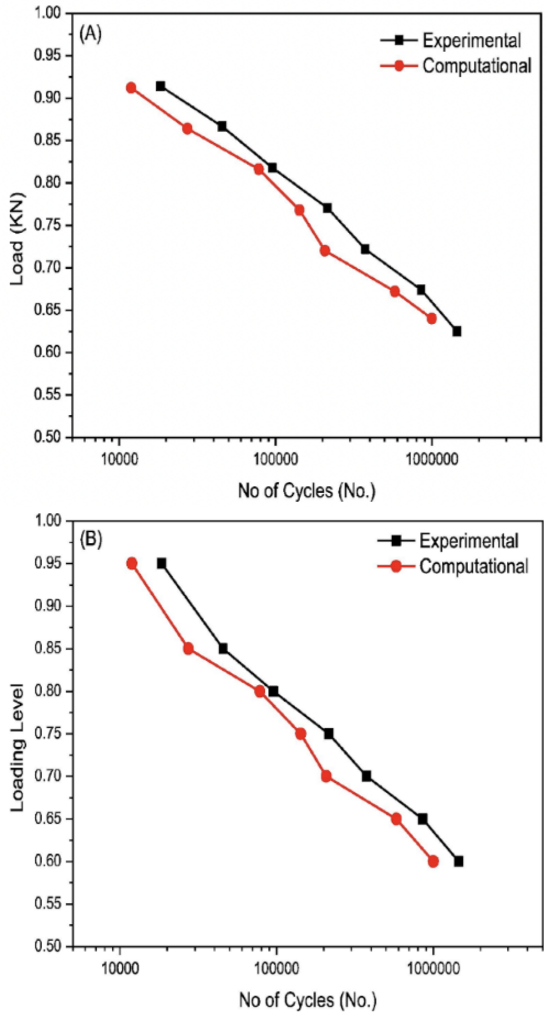


Fig. 13. Fatigue testing results: (**a**) load versus number of cycle response; (**b**) loading level (ratio of ultimate static and applied fatigue load) versus number of cycles [44].

Furthermore, it was argued by Hussain, Khan, and Abbas that a loading level of around 0.60 is appropriate for honeycomb structures to achieve the ideal fatigue performance. The findings indicate that this model can be used appropriately to determine fatigue life, flexural strength, and modes of failure for samples examined under both static and fatigue loading conditions [31, 44].

## 6. Conclusion

The mechanical behaviour of sandwich composite constructions with honeycomb core is reviewed in this paper.

(1) When compared to Acrylonitrile Butadiene Styrene (ABS) and other multilayer specimens, it

is shown that 3D printed Polylactic Acid (PLA) has a higher ultimate tensile strength.

(2) ABS outperformed PLA in terms of flexural strength and elongation before breaking. The layer thickness of 3D printed materials also has an effect on the strength values. The strength values are also affected by the layer thickness of 3D printed materials.

(3) When compared to the non-auxetic structure, the honeycomb core with auxetic behaviour exhibits superior mechanical properties, including greater bending stiffness in specified directions, increased buckling loads, and reduced modal densities in certain ranges.

(4) Re-entrant honeycomb cores are a unique material with negative Poisson's ratio behaviour in-plane.

(5) The thickness of the face sheet and the order in which the face sheets were stacked had an influence on bending performance.

(6) It has been established that using finite element analysis, the bending performance and fatigue behaviour of sandwich beams with honeycomb cores can be predicted.

The review given here offers fresh insights into the creation of sandwich composite structures with distinct mechanical characteristics for a variety of mechanical and structural applications.

## Acknowledgement

The present study was financially supported by Thailand and research funding provided through the Composite Structures Research Unit, Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Thailand.

## References

[1] W. Xingyu, J. Xiong, J. Wang, and W. Xu, "New advances in fiber-reinforced composite honeycomb materials," *Sci China Technol Sci*, vol. 63, pp. 1348-1370, Jul. 2020.

[2] S. M. Sajadi et al., "Multiscale geometric design principles applied to 3D printed schwarzites," *Adv Mater,* vol. 30, no. 1, p. 1704820, Nov. 2017.

[3] F. Tarlochan, S. Ramesh, and S. Harpreet, "Advanced composite sandwich structure design for energy absorption applications: Blast protection and crashworthiness," *Compos B Eng*, vol. 43, no. 5, pp. 2198-2208, Jul. 2012.

[4] T. Li and L. Wang, "Bending behavior of sandwich composite structures with tunable 3D-printed core materials," *Compos Struct*, vol. 175, pp. 46-57, Sep. 2017.

[5] B. L. Buitrago, C. Santiuste, S. Sánchez-Sáez, E. Barbero, and C. Navarro, "Modelling of composite sandwich structures with honeycomb core subjected to high-velocity impact," *Compos Struct*, vol. 92, no. 9, pp. 2090-2096, Aug. 2010.

[6] S. Huang, P. Liu, A. Mokasdar, and H. Liang, "Additive manufacturing and its societal impact: A literature review," *Int J Adv Manuf Technol,* vol. 67, pp. 1191-1203, Jul. 2012.

[7] S. K. Dhinesh, P. S. Arun, K. K. L. Senthil, and A. Megalingam, "Study on flexural and tensile behavior of PLA, ABS and PLA-ABS materials," *Mater Today: Proc*, vol. 45, pp. 1175-1180, Jan. 2021.

[8] M. Bazli and M. Abolfazli, "Mechanical properties of fibre reinforced polymers under elevated temperatures: An overview," *Polymers*, vol. 12, Nov. 2020.

[9] R. Lakes and K. J. Elms, "Indentability of Conventional and negative Poisson's ratio foams," *J Compos Mater,* vol. 27, no. 12, Jul. 1992.

[10] A. Abbadi, Z. Azari, S. Belouettar, J. Gilgert, and P. Freres, "Modelling the fatigue behaviour of composites honeycomb materials (aluminium/aramide fibre core) using four-point bending tests," *Int J Fatigue,* vol. 32, no. 11, pp. 1739-1747, Nov. 2010.

[11] A. Bandyopadhyay, S. Vahabzadeh, A. Shivaram, and S. Bose, "Three-dimensional printing of biomaterials and soft materials," *MRS Bull,* vol. 40, no. 12, pp. 1162-1169, Dec. 2015.

[12] N. Saad and A. Sabah, "An investigation of new design of light weight structure of (ABS/PLA) by using of three dimensions printing," in *Proceedings of the 13th International Conference "Standardization, Prototypes and Quality: A Means of Balkan Countries' Collaboration"*, Brasov, Romania, November 2016, vol. 17, no. 3, pp. 3-4.

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

[14] C.-C. Wang, T.-W. Lin, and S.-S. Hu, "Optimizing the rapid prototyping process by integrating the Taguchi method with the Gray relational analysis," *Rapid Prototyp J*, vol.13, no. 5, pp. 304-315, Oct. 2007.

[15] B. M. Tymrak, M. Kreiger, and J. M. Pearce, "Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions," *Mater Des*, vol. 58, pp. 242-246, Jun. 2014.

[16] A. K. Sood, R. K. Ohdar, and S. S. Mahapatra, "Parametric appraisal of mechanical property of fused deposition modelling processed parts," *Mater Des,* vol. 31, no. 1, pp. 287-295, Jan. 2010.

[17] J. Nomani, D. Wilson, M. Paulino, and M. I. Mohammed, "Effect of layer thickness and cross-section geometry on the tensile and compression properties of 3D printed ABS," *Mater Today Commun,* vol. 22, p. 100626, Mar. 2020.

[18] H. Ashrafi, M. Bazli, and A. V. Oskouei, "Enhancement of bond characteristics of ribbed-surface GFRP bars with concrete by using carbon

fiber mat anchorage," *Constr Build Mater,* vol. 134, pp. 507-519, Mar. 2017.

[19] R. J. A. Hamad, M. A. Megat Johari, and R. H. Haddad, "Mechanical properties and bond characteristics of different fiber reinforced polymer rebars at elevated temperatures," *Constr Build Mater,* vol. 142, pp. 521-535, Jul. 2017.

[20] L. J. Gibson and M. F. Ashby, in *Cellular Solids: Structure and Properties*, 2nd ed. Cambridge: Cambridge University Press, 1997.

[21] T. Li, Y. Chen, X. Hu, Y. Li, and L. Wang, "Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties," *Mater Des,* vol. 142, pp. 247-258, Mar. 2018.

[22] W. Miller, C. Smith, F. Scarpa, H. Abramovich, and K. Evans, "Multifunctional chiral negative poisson's ratio (auxetic) honeycomb cores with embedded piezo-ceramic patches," Jan. 2009.

[23] F. Scarpa and G. Tomlinson, "Sandwich structures with negative Poisson's ratio for deployable structures," in *IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, Dordrecht, pp. 335-343.

[24] H. Yazdani Sarvestani, A. H. Akbarzadeh, A. Mirbolghasemi, and K. Hermenean, "3D printed meta-sandwich structures: Failure mechanism, energy absorption and multi-hit capability," *Mater Des,* vol. 160, pp. 179-193, Dec. 2018.

[25] W. Hao, J. Xie, and 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, May. 2018.

[26] M. Sun, D. Wowk, C. Mechefske, and 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, Jul. 2019.

[27] S. V. Iyer, R. Chatterjee, M. Ramya, E. Suresh, and K. Padmanabhan, "A comparative study of the three point and four point bending behaviour of rigid foam core glass/epoxy face sheet sandwich composites," *Mater Today: Proc,* vol. 5, no. 5, pp. 12083-12090, Jan. 2018.

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

[29] M. Kaman, M. Solmaz, and K. Turan, "Experimental and numerical analysis of critical buckling load of honeycomb sandwich panels," *J Compos Mater,* vol. 44, pp. 2819-2831, Aug. 2010.

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

[31] Z. Li, Z. Wang, X. Wang, and W. Zhou, "Bending behavior of sandwich beam with tailored hierarchical honeycomb cores," *Thin-Walled Struct,* vol. 157, p. 107001, Dec. 2020.

[32] H. Fukuda, G. Itohiya, A. Kataoka, and S. Tashiro, "Evaluation of bending rigidity of CFRP skin-foamed core sandwich beams," *J Sadw Struct Mater,* vol. 6, pp. 75-92, Jan. 2004.

[33] C. Steeves, "Optimising sandwich beams for strength and stiffness," *J Sandw Struct Mater,* vol. 14, pp. 573-595, Sep. 2012.

[34] T. C. Triantafillou and L. J. Gibson, "Failure mode maps for foam core sandwich beams," *Mater Sci Eng,* vol. 95, pp. 37-53, Nov. 1987.

[35] J. Banghai, L. Zhibin, and L. Fangyun, "Failure mechanism of sandwich beams subjected to three-point bending," *Compos Struct,* vol. 133, pp. 739-745, Dec. 2015.

[36] A. Sakly, A. Laksimi, H. Kebir, and S. Benmedakhen, "Experimental and modelling study of low velocity impacts on composite sandwich structures for railway applications," *Eng Failure Anal,* vol. 68, pp. 22-31, Oct. 2016.

[37] J. Lu, G. Zou, Y. Cao, and B. Liu, "Investigation on fatigue behaviors of a honeycomb sandwich panel with initial debonding defects," *Harbin Gongcheng Daxue Xuebao/Journal of Harbin Engineering University,* vol. 33, pp. 325-329, Mar. 2012.

[38] I. Ben Ammar, C. Karra, A. El Mahi, R. el Guerjouma, and M. Haddar, "Mechanical behavior and acoustic emission technique for detecting damage in sandwich structures," *Appli Acoust,* vol. 86, pp. 106–117, Dec. 2014.

[39] A. Abbadi, C. Tixier, J. Gilgert, and Z. Azari, "Experimental study on the fatigue behaviour of honeycomb sandwich panels with artificial defects," *Compos Struct,* vol. 120, pp. 394-405, Feb. 2015.

[40] R. Lakes, "Foam Structures with a Negative Poisson's Ratio," *Science,* vol. 235, no. 4792, pp. 1038-1040, Feb. 1987.

[41] A. Bezazi and F. Scarpa, "Tensile fatigue of conventional and negative Poisson's ratio open cell PU foams," *Int J Fatigue,* vol. 31, no. 3, pp. 488-494, Mar. 2009.

[42] K. Essassi, J.-l. Rebiere, A. El Mahi, M. A. Ben Souf, A. Bouguecha, and M. Haddar, "Experimental and analytical investigation of the bending behaviour of 3D-printed bio-based sandwich structures composites with auxetic core under cyclic fatigue tests," *Compos – A: Appl Sci Manuf,* vol. 131, p. 105775, Apr. 2020.

[43] B. Wahid, B. Abderrezak, and F. Scarpa, "Identification and prediction of cyclic fatigue behaviour in sandwich panels," *Measurement,* Jul. 2014.

[44] M. Hussain, R. Khan, and N. Abbas, "Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load," *J King Saud Univ Sci,* vol. 31, no. 2, pp. 222-229, Apr. 2019.

DOI:10.4186/ej.2022.26.6.27

**Dechawat Wannarong** was born in Chonburi, Thailand in 1998. He received the Bachelor Degree in mechanical engineering from The University of Nottingham, Nottingham, United Kingdom in 2020. He also obtained another Bachelor Degree in mechanical engineering from Thammasat University, Bangkok, Thailand in 2020.

His research interests include bending behaviour, the solid mechanics and the composite structures.

**Thanyarat Singhanart** was born in Bangkok, Thailand in 1976. She received the B.Eng in mechanical engineering from Chulalongkorn University, Bangkok, Thailand in 1998 and M.Eng. in aeronautics and astronautics from Tokyo University, Tokyo, Japan in 2002 and the Ph.D. degree in aeronautics and astronautics from Tokyo University, Tokyo, Japan in 2005.

Sine 1998, she has been an instructor with Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand. Her research interests include stress analysis, fatigue, vibration, damping of composite materials and solid mechanics.