Research Article • DOI: 10.2478/ftee-2022-0010 FTEE • 151(2) • 2022 • 75–81

# Comparison of the Bending Resistance Properties of Carbon Fiber/Foam Sandwich Structural Composites with Different Laying Angles

Lvtao Zhu[1,2,3], Shengbin Cao[4]*, Xiaofeng Zhang[4], Wei Shen[3], Chengyan Zhu[1]

[1] College of Textile Science and Engineering (International Institute of Silk), Zhejiang Sci-Tech University, Zhejiang Province 310018, P.R. China
[2] Key Laboratory of Clean Dyeing and Finishing Technology of Zhejiang Province, Zhejiang Province 312000, P.R. China
[3] Shaoxing Baojing Composite Materials CO., LTD, Shaoxing, Zhejiang Province 312000 P.R. China
[4] School of Materials Science, Shanghai Dianji University, Shanghai 201306, P.R. China
* Corresponding author. E-mail: caosb@sdju.edu.cn

**Abstract**
This research aimed to explore the influence of fiber laying angles on the bending resistance properties of carbon fiber/foam sandwich structural composites. Four kinds of composites with the following laying angles: $[0°]_8$, $[0°/45°/90°/-45°]_s$, $[0°/90°]_4$ and $[45°/-45°]_4$ were prepared and tested in three-point bending experiments. The results obtained showed that the bending resistance performance was the best when the laying angle was $[0°]_8$, while it was the worst when the laying angle was $[45°/-45°]_4$. Besides, it was found that the tensile performance was the best when the fibers were arranged in the 0° direction when the strength utilisation rate was the highest. In addition, by observing the failure morphologies of the composites, the delamination and foam cracking were found in the four groups of composites. In contrast, the phenomenon of significant fracture was found on composites with a laying angle of $[45°/-45°]_4$ only, indicating it had a poor bending resistance performance.

**Keywords**
sandwich structure; composite; carbon fiber; ply angle; three-point bending.

## 1. Introduction

Sandwich structural composites are generally composed of two thin panels with high mechanical strength at the edges and a lightweight core layer with a weak load-bearing capacity [1, 2]. As shown in Figure 1, the sandwich structure can be divided into panels, core layers and a glue layer. The panel's function is mainly to provide high tensile and bending strength as well as in-plane tension and compression strength [3]. Therefore, the performance of this type of structural composites mainly depends on the upper and lower panels, especially on their arrangement [4]. The core layer is mainly used to connect the upper and lower panels, which simultaneously bears the shear load. Choosing appropriate core materials can reduce the structural weight and improve structural efficiency [5]. In the design of sandwich structural composites, materials with higher strength and rigidity can be selected for the panel, such as metal [6], stone slabs [7], high-performance fibers and their composites [8], etc. Weight reduction and better shear and compression properties should be considered for the core layer. Therefore, materials with lower density, such as foam plastic [9], honeycomb structure [10], wood material [11] and so on, can be selected as the core layers. Because sandwich structural composites have the advantages of high bending stiffness and light-weight, they have been widely used in medical equipment, aerospace, sports, wind power and other fields [12, 13].

At present, high-performance fibers are often used as raw materials to obtain fiber-reinforced sandwich composites with excellent mechanical properties. High-performance fibers include aramid, carbon fibers, glass fibers, etc. Among them, the density of carbon fiber is lower than that of aramid and glass fiber, being only 1.5~2.0 g/cm³ [14]. The tensile strength and modulus of carbon fiber are greater than for aramid fiber and glass fiber, reaching 3.8~5.5 GPa and 180~220 GPa, respectively [15]. In addition, carbon fibers also have the advantages of high-temperature resistance, radiation resistance, and a low thermal expansion coefficient [16]. Therefore, carbon fiber products can be applied to the bearing structure of aircraft wings and tail beams, as well as for the structural reinforcement

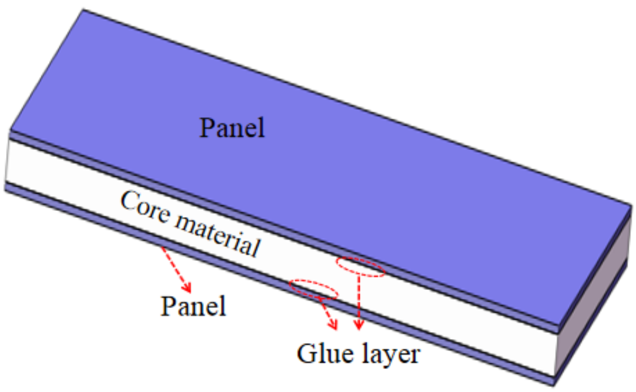


*Fig. 1. Schematic diagram of sandwich structure*

of beams and plates in civil engineering. However, the price of carbon fibers is relatively high.

In recent years, research on sandwich composites composed of carbon fibers and foam has attracted more attention from researchers. The specific forming process can be used to obtain excellent mechanical properties. For example, Hou et al. [17] used 3D printing technology to prepare sandwich structural composites. Compared with the traditional process, the automation was higher, and the structure had fewer defects and lower structural performance dispersion. Xiong et al. [18] prepared carbon fiber sandwich composites with different densities using the mould hot-pressing integrated moulding process, analyzed three possible failure modes, and deduced the shear strength. Liu et al. [19] prepared carbon fiber reinforced sandwich structural composites, where the rod ends were dispersed and embedded in the middle of the upper and lower panels, which effectively improved the mechanical properties. Nobe et al. [20] obtained a the carbon fiber/polypropylene foam composite using microcellular injection moulding technology, and studied the effects of injection moulding conditions and the number of carbon fibers on the bending and impact properties. Feng et al. [21] realised a carbon fiber reinforced square honeycomb foam sandwich structure through a simple buckle and bonding method, which increased the specific compressive strength by approximately 330% and the specific shear strength by approximately 180%.

Some researchers have used sandwich foam materials to modify or add other substances to enhance the mechanical properties of the core layer [22, 23]. For example, Schfer et al. [24] used rigid and flexible polyurethane foams to make thermoplastic composite interlayers and reinforced them with spacer fabrics. This efficient process allows to produce complex structures in large quantities. Smorygo et al. [25] added short carbon fibers and aluminum powder to the epoxy foam to form an open-cell structure interlayer. This interlayer increased the compressive strength by 12-15% compared with pure epoxy foam. Wang et al. [26] incorporated carbon fiber into hollow glass microsphere-epoxy composite foam as the mechanical reinforcement phase of the core layer. They studied the effect of carbon fiber orientation on the fiber elastic modulus and stress distribution. It was found that the elastic modulus of the matrix reaches the maximum value of 434 MPa, and that the enhancement effect was the best.

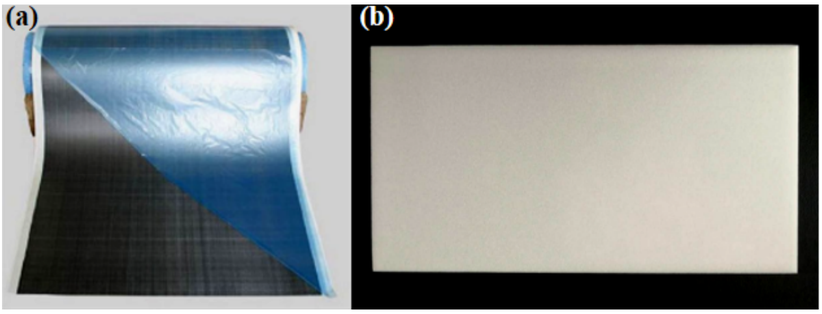


*Fig. 2. (a) Carbon fiber unidirectional prepreg, and (b) PMI foam board*

Bending performance is one of the leading mechanical properties of composites. In engineering applications, composite components are often subjected to bending loads. The mechanical failure behaviour of composites under bending affects the service life of structural engineering parts. Therefore, the three-point bending testing method is often used to study the bending properties of composites. Pandey et al. [27] prepared carbon fiber/foam core sandwich composites. The three-point bending tests showed that the bearing capacity was eight times higher than that of the bare foam structure, and the bending stiffness was nine times higher. Liu et al. [28] analyzed the three-point bending failure of carbon fiber reinforced Y-shaped frame sandwich composites. The results showed that the value of P/delta was comparable to that of the Y-shaped sandwich frame. Kiyak et al. [29] studied the three-point bending mechanical properties of a new type of carbon fiber sandwich composite. The results provide a basis for determining the best peak load/density ratio of different core sandwich composite materials. Kentaro et al. [30] used continuous carbon fiber 3D printers to manufacture honeycomb, diamond, rectangular and round core sandwich structures. Through shape evaluation and three-point bending tests, the functional properties of the sandwich structure were quantified.

In this paper, four kinds of carbon fiber/foam sandwich structural composites with the laying angles include $[0°]_8$, $[0°/45°/90°/-45°]_s$, $[0°/90°]_4$ and $[45°/-45°]_4$ were prepared and tested in three-point bending experiments. By evaluating the influence of the laying angles on the bending resistance performance, failure mode and failure mechanism, it provides a practical structural optimisation approach for the bending resistance performance of sandwich structural composites.

## 2. Experimental

### 2.1. Materials

Carbon fiber/epoxy unidirectional prepreg and PMI foam board were selected to manufacture sandwich composite materials (Figure 2). The prepreg was supplied by Shandong Jiangshan Fiber Technology Co., Ltd. and the PMI foam by Hangzhou Wincarb New Material Technology Co., Ltd. The specifications of the carbon fiber unidirectional prepreg and mechanical parameters of the PMI foam board are listed in Tables 1 and 2, respectively.

### 2.2. Preparation of the carbon fiber/PMI foam sandwich structural composites

The vacuum assisted moulding process (Vacuum Assisted Resin lnfusion, VARI) was used to obtain the composite specimens. VARI is a new composite molding process developed based on Resin Transfer Moulding (RTM). The method involved laying the prepreg and foam core in a particular layer on the mould, and then sealing it with a flexible film bag. A vacuum pump was used to exhaust the air in the fibers, and then it was put it in an oven for curing and forming, thereby obtaining foam sandwich structural composites. Figure 3 presents the heating and curing process of sandwich structural composite fabrication.

According to the different laying methods, the specimens were divided into four groups. The specific laying methods of each group are listed in Table 3. The fiber-reinforced foam sandwich structural composites are shown in Figure 4.

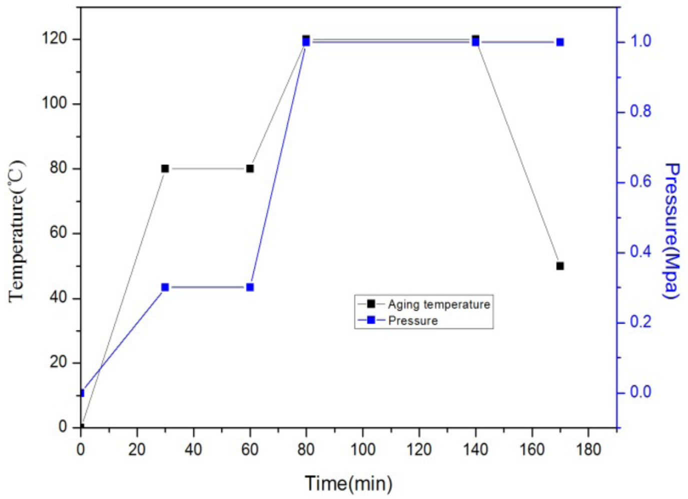


*Fig. 3. Heating and curing process*

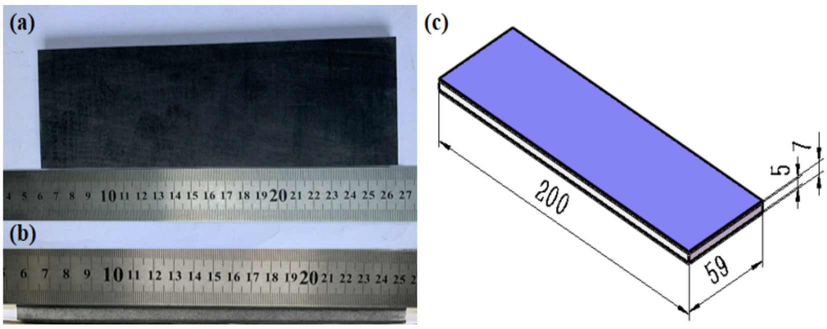


*Fig. 4. Carbon fiber/PMI foam sandwich structural composite (a) top view, (b) side view and (c) size (mm)*

| Carbon yarn weight (g/m²) | Resin content (g/m²) | Resin weight (g/m²) | Gross weight (g/m²) | Thickness *(mm)* |
|---|---|---|---|---|
| 150 | 32 | 71 | 221 | 0.150 |

*Table 1. Specifications of the carbon fiber unidirectional prepreg*

## 2.3. Three-point bending tests

An MTS materials testing machine was used for performing three-point bending tests. The size of each specimen was 200×59×7 mm (length×width×thickness), as shown in Figure 5. The bending experiments were carried out with five specimens in each group.

The three-point bending tests were conducted according to the GB/T 1456-2005 testing standard, with a span of 120 mm and loading speed of 5 mm/min.

In addition, the bending strength and bending stiffness of the sandwich structural composites can be calculated according to the Equation 1.

$$\sigma_f = \frac{P \bullet L}{4b \bullet t_f (h - t_f)} \quad (1)$$

Where: P - Load (N); L -Span (mm); b - Width of the specimen (mm); $t_f$ - Panel thickness (mm); h - Thickness of the specimen (mm).

## 3. Results and discussions

### 3.1. Three-point bending mechanical properties

Figure 6 shows the bending process of the composites of Group A, and the load-displacement curves are shown in Figure 7. It can be seen that in the initial stage of the specimen being stressed, the curve shows a linear upward trend; that is, as the deformation increases, the load also shows a linear upward state. From then, due to the increase in the deformation of the core layer structure, the stress concentration effect at the center becomes obvious, causing the stress to reach the threshold, whereby microcracks begin to sprout and propagate, and damage begins to occur. The sound caused by the damage

| Density (kg/m³) | Elastic modulus (MPa) | Poisson's ratio | Shear modulus (MPa) | Tensile strength (MPa) | Compressive strength (MPa) | Shear strength (MPa) | Elongation at break (%) |
|---|---|---|---|---|---|---|---|
| 75 | 92 | 0.3 | 29 | 2.8 | 1.5 | 1.3 | 3.0 |

*Table 2. Mechanical parameters of the PMI foam board*

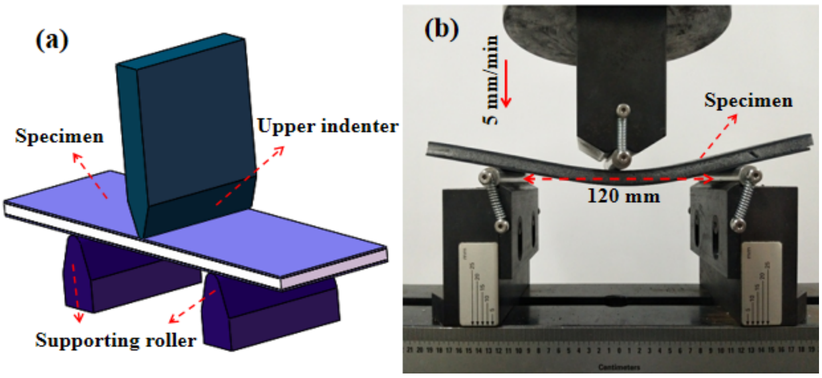


*Fig. 5 Three-point bending testing setup: (a) schematic diagram and (b) experimental photo*

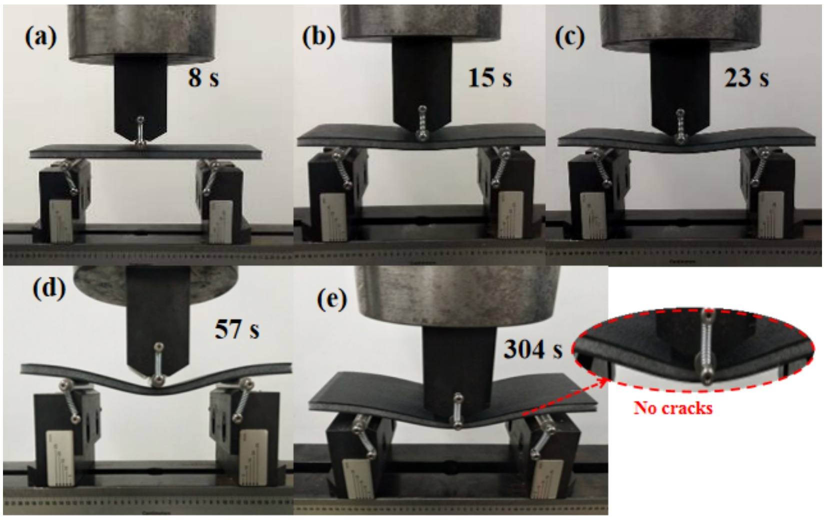


*Fig. 6. The bending process of the composite Group A*

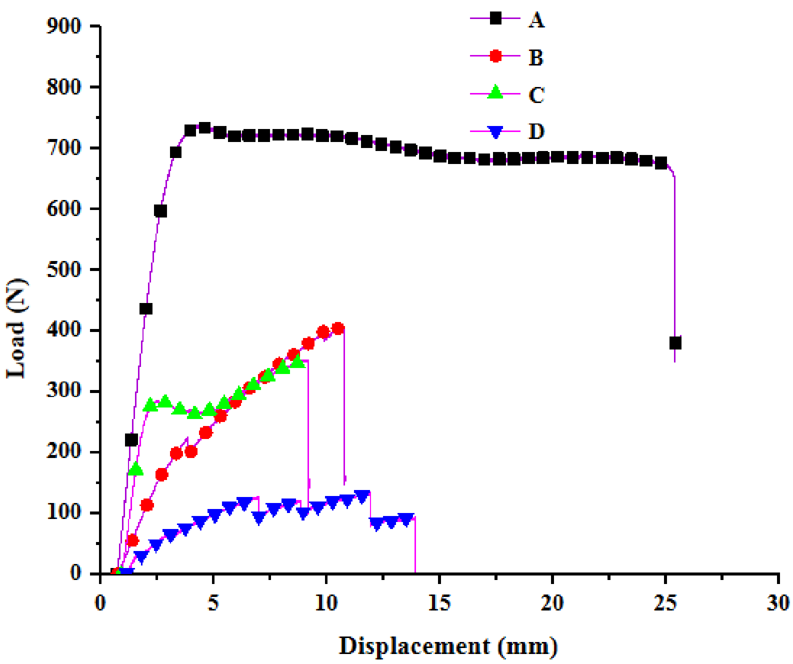


*Fig. 7. Displacement-load curves*

| Specimen | Laying angle |
|---|---|
| A | $[0°]_8$ |
| B | [0°/45°/90°/-45°]s |
| C | $[0°/90°]_4$ |
| D | $[45°/-45°]_4$ |

*Table 3. Laying methods for the specimens tested*

can be heard. At this moment, the load no longer increases and indicates a slight decrease, but the amount of deformation increases rapidly. Finally, when the specimen is further damaged, the main body of the structure can no longer bear the external load, and the material eventually fails. This phenomenon is reflected in the curve; that is, the load value suddenly drops.

Figure 8 shows the failure process of the composites of group B in which the curve shows a linear relationship in the early stage. This phenomenon shows that an increase in the deformation requires a continuous increase in the load, which is closely related to the structure of the panel. In addition, the core layer structure has evident cracking at approximately 48 s, indicating that the composite has absorbed the energy brought by the external load, and there is a noticeable fluctuation in the curve since the load continues to increase. At 129 s, the lower panel separates from the core foam when the load reaches the maximum value. Because the specimen has failed, it can no longer bear the load.

Figure 9 shows the failure process of the composite in group C. It can also be seen that the curve shows a linear relationship and the load continues to increase at the stage before the specimen is damaged. The core structure cracked at approximately 31 s. At this time, the load reaches a small peak, and then it begins to drop slightly.

However, after a slight drop in the load, it increases slowly. At approximately 110 s, the lower panel separated from the foam. At this time, the load reached the maximum value and the specimen was finally damaged.

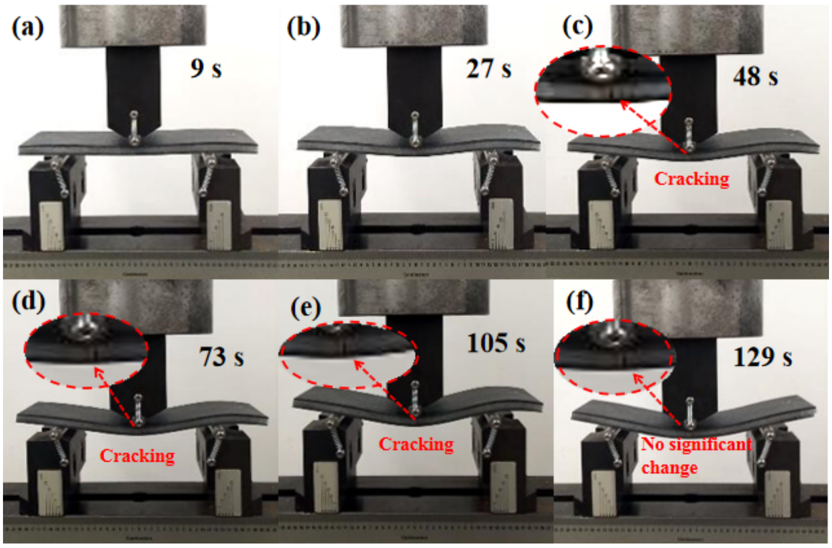


*Fig. 8. Bending process of the composite group B*

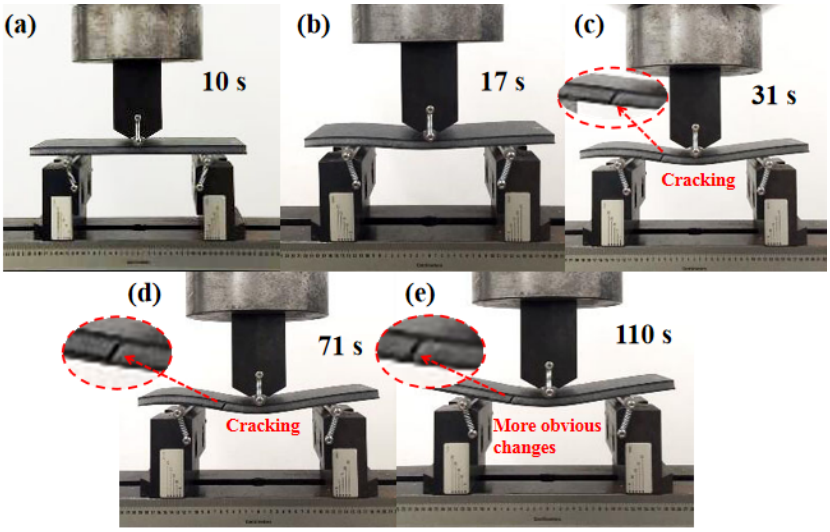


*Fig. 9. Bending process of the composite group C*

| Group | Laying angle | Failure load (N) | Bending strength (MPa) |
|---|---|---|---|
| A | $[0°]_8$ | 762.67 | 64.63 |
| B | $[0°/45°/90°/-45°]_s$ | 454.23 | 38.49 |
| C | $[0°/90°]_4$ | 355.80 | 30.15 |
| D | $[45°/-45°]_4$ | 92.47 | 7.84 |

*Table 4. Obtained results of sandwich structural composites tested*

Figure 10 shows the damage process of composite group D. It can be seen that the curve shows a linear relationship in the initial stage, and the load continues to increase. The core foam structure cracks at approximately 84 s and simultaneously absorbs a certain amount of energy, which induces the load to drop with a small magnitude. As the loading process continues, the load increases again. At 143 s, the foam separates from the lower panel. At this moment, the load drops rapidly again due to energy absorption. At approximately 167 s, the composite is completely damaged.

### 3.2. Influence of laying angles

In Figure 7, it can also be seen that the composite group A shows the most stable structure, and the required time from the core cracking to complete failure was the longest, which means the bending resistance performance was the strongest. Simultaneously, the composite group D was the weakest. In the testing process, the panel structures of composite group D were damaged, which indicates composite group D has the worst bending resistance performance.

In addition, because of the different laying angles, the specific mechanical properties were also different. Table 4 lists the sandwich composites' failure strength, bending strength, and bending stiffness at different laying angles. Under the three-point bending load, the upper panel bears the compression load and the lower panel the tensile load. As we know, the tensile strength of the composite is greatest along the fiber direction. It can be seen that the failure strength of composite group A is much greater than the others. The carbon fiber/PMI foam sandwich composite with a ply angle of $[0°]_8$ has the maximum bending resistance strength, and the composite with a ply angle of $[45°/-45°]_4$ - the minimum bending resistance strength. The bending strength of the composites at different laying angles was as follows.

$$[0°]_8 > [0°/45°/90°/-45°]_s > [0°/90°]_4 > [45°/-45°]_4$$

## 4. Conclusions

In this research, four kinds of composites with laying angles of $[0°]_8$, $[0°/45°/90°/-45°]_s$, $[0°/90°]_4$ and $[45°/-45°]_4$ were prepared and tested in three-point bending experiments to study the influence of laying angles on the bending resistance properties of carbon fiber/foam sandwich structural composites.

1. The overall bending properties of carbon fiber/PMI foam sandwich structural composites depend not only on their material constituents but also on their arrangement. The sandwich structural composite with a

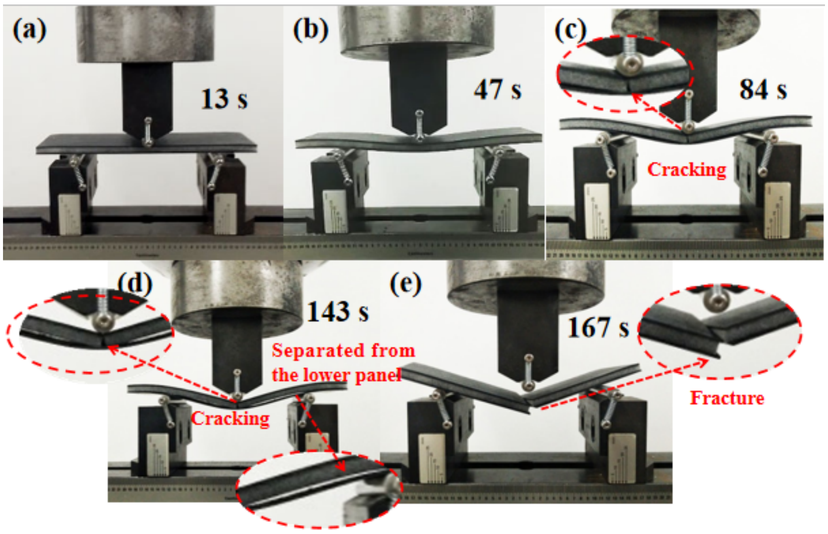


*Fig. 10. Bending process of the composite group D*

laying angle of $[0°]_8$ takes the longest time to failure, indicating that it can maintain long-term stability after cracks are found in the core layer. It shows that its bending resistance performance is relatively excellent.

2. The laying angles have a significant impact on the mechanical properties of the sandwich structure. When the direction of fiber distribution tends towards the X-axis (the 0° direction), the mechanical properties of the fibers are fully utilized; thus, it shows the better bending resistance performance.
3. By observing the failure morphologies of the composites, delamination and foam cracking can be found in the four groups of composites, while the phenomenon of significant fracture can be found on the composites with a laying angle of $[45°/-45°]_4$ only, indicating it has a poor bending resistance performance.


## Acknowledgements

This work was supported by the Zhejiang Provincial Natural Science Foundation of China under Grant No. LGG21E050025, the Fundamental Research Funds of Zhejiang Sci-Tech University (Project Number: 20202113-Y), Teacher Professional Development Project of Shanghai Municipal Education Commission 2020 Shanghai Higher Education Teacher Training Plan, the Fundamental Research Funds of Shaoxing Keqiao Research Institute of Zhejiang Sci-Tech University (Project number: KYY2021001G), as well as the Open Project of the State Key Laboratory of Non-ferrous Metal Material Preparation and Processing (No:19AZ02). We also acknowledge the support from the Open Project of Key Laboratory of Silk Engineering of Jiangsu Province (No. KJS2059).


## References


1. Endres GC, Weber HJ. U. S. Patent 083389, 2005.
2. Zhang W, Qin QH, Li JF, Su BH Zhang JX. *Composites Part B*, 2020; 201.
3. Hochet N, Vendangeot F. European Patent 0989932, 2003.
4. Fedon N, Weaver PM, Pirrera A, Macquart T. *Composites Part C:* Open Access, 2021; 4.
5. Yang DX, Hu YC, Fan CS. *Journal of West China Forestry Science* 2019; 48: 16.
6. Sun GY, Wang Z, Yu H, Gong ZH, Li Q. *Composite Structures* 2019; 209, 535.
7. Sullivan CC. *Building Design & Construction* 2018; 9, 65.
8. Peijs A, Jacobs M, Lemstra PJ. *Comprehensive Composite Materials* II, 2018; 1, 86.
9. Fatt MSH, Alkhtany M, Sirivolu D. *Composite Sandwich Structures* 2018; 265.
10. Tang E, Zhang X, Han Y. *International Journal of Structural Stability & Dynamics* 2020; 20.
11. Hussain M, Abbas N, Zahra N, Sajjad U, Awan MB. *Sn Applied Ences* 2019; 1: 875.
12. Manalo AC, Aravinthan T, Karunasena W. *Construction and Building Materials* 2013; 47.
13. Selvaraj R, Ramamoorthy M, Arumugam AB. *Composite Structures* 2021; 277.
14. Stokke RM, Jertson MR, Schweigert BD, U. S. Patent 006589, 2015.
15. M. Endo, H. Takiyama, and N. Andou, Japan Patent, 087992 (2005).
16. Dong C, Kai L, Jiang Y, Dwayne A, Zhang D. *Optics Express* 2018; 26:531.
17. Hou Z, Tian X, Zhang J, Li D. *Composite Structures* 2018; 184: 1005.
18. Xiong J, Ma L, Pan S, Wu L, Vaziri A. *Acta Materialia* 2012; 60: 1455.
19. Liu J, Xiang L, Kan T. *Composites Part A: Applied Science and Manufacturing* 2015; 79: 146.
20. Nobe R, Qiu J, Kudo M, Zhang G. *Polymer Engineering and Science* 2020; 60: 1507.
21. Feng LJ, Yang ZT, Yu GC, Chen XJ, Wu LZ. *Composite Structures* 2018; 201: 845.
22. Wu Q, Ma L, Wu L, Xiong J. *Composite Structures* 2016; 153: 585.
23. Waddar S, Pitchaimani J, Doddamani M. *Polymer Composites* 2020; 41: 1774.
24. Schfer K, Nestler D, Jahn K. Jentzsch H, Kroll L. *Key Engineering Materials* 2019; 809, 277.
25. Smorygo O, Mikutski V, Marukovich A, Sadykov V, Bespalko Y, Stefan A, Pelin CE. *Composite Structures* 2018; 202: 917.
26. Wang Y, Ya B, Zhou B, Meng L, Zhang X. *Journal of Applied Polymer Science* 2019; 136: 47083.

27. Pandey A, Muchhala D, Kumar R, Sriram S, Venkat ANC, Mondal DP. *Composites*, 2020; 183: 107729.1.
28. Liu J, He Z, Liu J, Huang W. *Thin-Walled Structures* 2019; 145: 106387.1.
29. Kiyak B, Kaman MO. *Journal of Composite Materials* 2018; 53: 3093.
30. Kentaro S, Ryosuke M, Masahito U, Akira T, Yoshiyasu H. *Composites Part A Applied Science & Manufacturing* 2018; 113, 114.