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Flexural properties of lightweight carbon fiber/epoxy resin composite sandwiches with different fiber directions

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Abstract

In this study, structurally efficient carbon fiber reinforced plastic (CFRP) sandwiches were developed via introducing pumice/Mg composite foams as new core material. The effects of the fiber direction (0°, 45°, 90°) on the mechanical properties of CFRP laminates and composite sandwiches were studied. Compared with 45°-CFRP and 90°-CFRP laminates, 0°-CFRP laminate exhibits outstanding flexural properties due to different failure modes. Correspondingly, the 0°-CFRP/PMSF composite sandwiches exhibit higher flexural strength than 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches. The as-prepared composite sandwiches are lightweight and have higher specific strength than some traditional sandwiches. The different flexural behaviors of three types of sandwiches were observed to explain the failure mechanisms.

1. Introduction

Over the past decades, sandwich panels have drawn considerable attention attributed to the urgent demand for lightweight materials with high specific strength and stiffness [1, 2]. The typical sandwich panels are composed of a lightweight core and two high-strength skins (face sheets) [3]. These materials are prominently used in automotive, aerospace, and marine applications [4, 5].

The skin materials and core materials play a crucial role in the mechanical properties of the sandwiches. In previous studies, various skin materials and core materials were used to fabricate sandwich panels [6–19]. The skin materials are usually made of relatively high-strength materials, e.g. metal [11, 13], fiber-reinforced plastic [6, 15], ceramic material [10, 16], and carbon fiber-reinforced plastics (CFRP) and aluminum sheet are mostly common used [17, 18]. The CFRP laminate is lightweight (1.6g/cm³), and it is easy to obtain the required mechanical properties by adjusting the fiber-epoxy layer structure. The flexural responses of CFRP composite sandwiches depend largely on the fiber direction, stacking sequence, and layer thickness of the CFRP skins [19]. Meanwhile, various types of core materials are selected to fabricate the CFRP composite sandwiches, such as Al foams (or honeycombs) [6, 19], balsa woods [20], PVC foam [6, 21], and Ayous wood [21], etc. The CFRP composite sandwiches with aluminum foam core are frequently-used in large scale. The studies on flexural deformation behavior, impact responses and compressive behavior indicated that the CFRP composite sandwiches with aluminum foam core have high strength and stiffness to weight ratios [4, 6, 19, 22, 23].

Although aluminum core materials have been used to prepare CFRP composite sandwiches, lightweight metallic core materials still need to be developed to fabricate the composite sandwiches with a high ratio of performance to weight. Mg alloy brings amazing application prospects in sandwiches attributed to the low density (~1.74 g/cm³), high specific strength, good damping. However, there is little information about the CFRP composite sandwiches filled with magnesium core so far. In this paper, CFRP composite sandwiches with
pumice/Mg core were fabricated. Three types of unidirectional CFRP laminates were used as skin materials, and the effect of CFRP skin types on the flexural properties of prepared CFRP composite sandwiches was investigated by the three-point bending test. Meanwhile, the deformation modes and failure mechanism of the CFRP laminates and corresponding composite sandwiches were also studied.

2. Material and methods

2.1. Materials

The unidirectional CFRP laminates were prepared using the carbon fiber prepreg (CF, ZFS Materials Co., Ltd) by hot-pressing method. The epoxy matrix in CFRP laminates will decompose rapidly when the temperature exceeds 300 °C (Extended data figure 1 [available online at stacks.iop.org/MRX/9/026506/mmedia] in supplementary information), so the service temperature of as-prepared CFRP laminates should not exceed this value. The stacking sequence of the plies is [0]_s and the thickness of obtained CFRP laminates is 2 mm. The macro photograph of an uncut CFRP laminate is shown in figure 1(a). According to the different fiber directions (0°, 45°, 90°) of the unidirectional CFRP laminate, the CFRP laminate can be divided into three types, i.e., 0°-CFRP, 45°-CFRP and 90°-CFRP, where the 0°-CFRP represents that the longitudinal carbon fiber direction, and the 90°-CFRP represents the transverse carbon fiber direction. The detailed schematic diagram of three types of CFRP laminates is shown in figure 1(b).

2.2. Sample preparation

The lightweight pumice/Mg core was fabricated by pressure-infiltration method. In short, the selected pumice particles with the size of 3–4 mm were transferred into a cylindrical mould. Then, the molten magnesium was infiltrated into the gaps between pumice particles under vertical pressure. After solidification, the pumice/Mg core was processed to the required size for subsequent experiments.

The preparation process of CFRP sandwich panels with pumice/Mg core is shown in figure 2. The length, width and thickness of the core material are 60 mm, 15 mm and 10 mm, respectively. The lightweight pumice/Mg core is between two thin CFRP skins, and the core material and CFRP skins are tightly bonded by epoxy adhesive under low pressure. After 24 h of curing, the composite sandwiches for the test were obtained. Three types of composite sandwiches with pumice/Mg core were obtained by using the CFRP skins with different fiber directions.

2.3. Tensile and bending tests

The tensile stress-strain curves of CFRP skins in three fiber directions (0°, 45°, 90°) were investigated using a universal testing machine (MTS810, USA) at a crosshead displacement rate of 2 mm/min. The three-point bending tests of different CFRP skins and corresponding sandwich panels were carried out using a universal testing machine (Instron 1121, USA) with a loading capacity of 10 kN. The three-point bending test and test

![Figure 1. (a) Macro view of the CFRP laminate and (b) schematic diagram of three types of CFRP face sheets.](image-url)
parameters are shown in figure 3. The specimens were supported by two supports with a span of 50 mm, and the crosshead displacement rate is 1 mm/min. The blue background is more conducive to obtaining high-quality sample photographs.

2.4. Characterization
The scanning electron microscope (SEM, JSM-5310, Japan) was employed to observe the microstructure of the samples. The energy-dispersive spectrum analyzer (EDS, Link-ISIS, UK) was used for element analysis.

3. Results and discussion

3.1. Structure and density of the CFRP composite sandwiches
Figure 4 shows the typical macroscopic morphology of pumice/Mg core and corresponding composite sandwiches. The pumice/Mg core is composed of Mg framework and porous pumice particles, similar to syntactic foam; therefore, they are also named pumice/Mg syntactic foam (PMSF). The composite sandwiches
with different fiber directions are named as $0^\circ$-CFRP/PMSF, $45^\circ$-CFRP/PMSF and $90^\circ$-CFRP/PMSF, respectively.

Figure 5 shows the SEM image and EDS analysis of the interface between the CFRP face sheet and PMSF core. The SEM image confirms a high porosity of pumice particles, making a low density of $\sim 0.89 \text{ g/cm}^3$ for PMSF core, which is conducive to obtaining lightweight sandwiches. Figures 5(b)–(d) show the corresponding distribution of C, Mg and Si elements, where C, Mg and Si can represent CFRP face sheet, magnesium matrix and pumice particle, respectively. The CFRP face sheet and the PMSF core are tightly bonded. The CFRP face sheet covering the surface of the core has the density of $1.6 \text{ g/cm}^3$. As a result, the PMSF core and CFRP face sheet provide lightweight CFRP composite sandwiches with the density of $\sim 1.14 \text{ g/cm}^3$.

3.2. Tensile properties of the CFRP laminate

Figure 6(a) shows the typical stress-strain curves of $0^\circ$-CFRP, $45^\circ$-CFRP and $90^\circ$-CFRP laminates. It can be seen that the stress of all specimens increases linearly with strain before CFRP failure. The $0^\circ$-CFRP specimen exhibits the most excellent tensile properties, and the tensile strength is about 1400 MPa. The tensile strengths of $45^\circ$-CFRP and $90^\circ$-CFRP are 100 MPa and 40 MPa, respectively. Correspondingly, the tensile moduli of $0^\circ$-CFRP, $45^\circ$-CFRP and $90^\circ$-CFRP are about 112 GPa, 12 GPa and 5 GPa, respectively. The experimental results demonstrate that the unidirectional CFRP is typically anisotropic, and its tensile properties in different fiber directions may differ by more than 10 times. This result is consistent with the reports in the previous study [24].

3.3. Flexural properties of the CFRP laminate

Figure 7(a) shows the typical load-displacement curves of three types of CFRP laminates under the bending test. The load of all samples increases linearly with displacement before the peak value. Similar experimental phenomena have been reported by other researchers [25]. For $0^\circ$-CFRP, when the load reaches the maximum value, the specimen begins to fail, and the load gradually decreases to a lower level with the increase of displacement. The flexural curves of $45^\circ$-CFRP and $90^\circ$-CFRP laminates are similar in shape. However, unlike $0^\circ$-CFRP, the $45^\circ$-CFRP and $90^\circ$-CFRP suddenly lose their bearing capacity when the load reaches the peak value, which is shown in the load-displacement curve as the load drops rapidly to 0 MPa. Flexural strength ($\sigma_f$) refers to the maximum stress that the material can bear under flexural load, and it is the main parameter to measure the flexural properties. The flexural strength of the tested specimens can be calculated using the following formula [26]:

$$\sigma_f = \frac{3P_{\text{max}}L}{2wt^2}$$

Where $P_{\text{max}}$ is the maximum load in the flexural load-displacement curves, $L$ is the support span, $w$ and $t$ represent the width and thickness of the specimen, respectively. The flexural strengths of $0^\circ$-CFRP, $45^\circ$-CFRP and $90^\circ$-CFRP are about 1300 MPa, 165 MPa and 100 MPa, respectively. Corresponding to tensile results, the three-point bending test also proves that unidirectional CFRP has obvious anisotropy, and its mechanical properties are quite different in different directions. Figures 7(b)–(d) show the optical images of the three types of CFRP after the bending test. It can be seen from figure 7(b) that the $0^\circ$-CFRP undergoes obvious flexural deformation after the bending test, but the specimen still maintains a relatively whole. In contrast, $45^\circ$-CFRP
Figure 5. The SEM image and EDS analysis of the interface between the CFRP face sheet and PMSF core.

Figure 6. Representative stress-strain curves of 0°-CFRP, 45°-CFRP and 90°-CFRP laminates.
and 90°-CFRP specimens are brittle fracture into two separate segments under flexural load (figures 7(c), (d)), which reflects the catastrophic drop of the load on the load-displacement curves. For 45°-CFRP and 90°-CFRP, once a crack appears in the resin, the crack will spread rapidly along the fiber direction, resulting in devastating fracture.

Under bending test, CFRP laminates may have various failure modes, such as matrix cracking, interfacial debonding, fiber breakage and delamination. The carbon fibers in 0°-CFRP, 45°-CFRP and 90°-CFRP laminates are perpendicular, 45° and parallel to the indenter, respectively. Since the strength of the epoxy matrix in CFRP laminates is much lower than that of carbon fibers, different failure modes occur during bending for different types of unidirectional CFRP laminates. Therefore, it is vital to discuss the failure modes of 0°-CFRP, 45°-CFRP and 90°-CFRP laminates for understanding the difference of their flexural properties. Figures 8(a)–(c) are SEM images of the side surfaces of the different types of CFRP laminates after bending test. Figure 8(a) shows that 0°-CFRP has obvious delamination (marked with arrow). Caminero et al [26] also reported similar results, and considered that the interlaminar shear failure would lead to lower flexural strength and stiffness than expected. The SEM images on the side surface of failed 45°-CFRP and 90°-CFRP specimens clearly show that the crack propagates strictly along the fiber direction. Figures 8(d)–(f) correspond to the fracture morphologies of 0°-CFRP, 45°-CFRP and 90°-CFRP, respectively. The fracture morphology of 0°-CFRP indicates that the carbon fibers are broken and pulled out. In contrast, the fracture morphologies of 45°-CFRP and 90°-CFRP demonstrate that the fibers are undamaged, and the cracking in the resin matrix and debonding at the fiber/matrix interface are the main failure modes. Previous studies have demonstrated that the flexural properties of CFRP laminates with the failure mode including fiber fracture are superior to those of specimens with the failure mode only including matrix cracking and interfacial debonding [26, 27].

3.4. Flexural properties of composite sandwiches

The typical load–displacement curves of PMSF core and three types of composite sandwiches under three-point bending test are shown in figure 9. Generally, the load–displacement curves of the specimens can be divided into two stages: the initial elastic flexural stage and the flexural collapse stage. In the initial stage, the load of all specimens increases linearly with the increase of displacement. This phenomenon is consistent with the results in other literature [19, 28]. For 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches, when the load reaches the maximum value, the load suddenly decreases due to the damage and failure of the specimens. In contrast, for 0°-CFRP/PMSF composite sandwiches, after reaching the peak value, there is a short plateau region. According to Formula (1), the flexural strengths of core material, 0°-CFRP/PMSF, 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches correspond to ~6.5 MPa, ~85 MPa, ~39 MPa and ~35.5 MPa respectively. The flexural properties of 0°-CFRP/PMSF composite sandwiches are more excellent than some traditional composite sandwiches reported in other papers [5, 13, 21], which means that it has a good application prospect. For example, the specific flexural strength (~74.6 MPa/ g·cm−3) of 0°-CFRP/PMSF composite sandwiches is about 5 times that of the aluminum foam sandwich (12–15 MPa/ g·cm−3) prepared by Zu et al [5] and 7 times that of aluminum foam core/stainless steel composite sandwiches (~10.5MPa/g·cm−3) prepared by Shunmugasamy et al [13]. For as-prepared composite sandwiches, the flexural strength of 0°-CFRP/PMSF...
composite sandwiches is higher than that of 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches. The different mechanical properties of composite sandwiches can be attributed to different types of CFRP skins. Finally, compared with 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches, 0°-CFRP/PMSF composite sandwiches have longer displacement from the beginning of the bending test to the complete failure, which is due to the better toughness of 0°-CFRP face sheets.

3.5. The failure behavior of composite sandwiches

To better understand the failure mode of prepared samples, photographs of the core material, 0°-CFRP/PMSF, 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches before the three-point bending test and at the onset of failure are presented in figure 10. Under the flexural displacement of 1.5 mm, the pumice particles in the PMSF core are broken, and the core material has obvious shear failure and cracks (marked by green ellipse),
which reduces the load-bearing capacity. At this time, the 0°-CFRP face sheets are not fractured, and the 0°-CFRP/PMSF specimen still has high load-bearing capacity, which can be observed in the load-displacement curve in figure 9. Zhang et al [29] and Pareta et al [28] also reported a similar failure mechanism in three-point bending tests of sandwich composites prepared by them. In contrast, samples 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches experience not only shear failure of the core material but also brittle fracture of the CFRP skin near the support point (marked by yellow ellipse), which leads to a significant decrease in the load-bearing capacity of 45°-CFRP/PMSF and 90°-CFRP/PMSF composite sandwiches. The bond strength between the core material and the skin significantly affects the propagation path of cracks in the resulting sandwich panel during bending [30]. When the bond strength is low, the sandwich panel will fail by debonding between the core material and the skin (especially the lower skin). When the interfacial bond strength is higher than the core shear strength, the core shear failure of the specimen occurs [31]. In this experiment, the PMSF core and CFRP skin have strong bonding strength, which can be attributed to the following reasons: (1). Unlike the metal foam core, the contact area between the PMSF core and the CFRP skin is large (2). High strength of the epoxy adhesive [31]. In the initial stage of the bending test, the CFRP skin and PMSF core are deformed together. When the displacement reaches a certain value, the PMSF core undergoes shear failure, and the cracks expand as the bending continues. At this time, due to the high bond strength between the PMSF core and CFRP skin, no obvious debonding occurred.

4. Conclusion

In this study, lightweight high-performance CFRP composite sandwiches with density of 1.14 g/cm³ were successfully fabricated by using pumice/Mg syntactic foams as core and CFRP laminate as skin. Mechanical tests indicate that the unidirectional CFRP laminates are obvious anisotropy, depending on the fiber direction. The main failure modes of 0°-CFRP are fracture and pull out of carbon fibers. In contrast, the main failure modes of 45°-CFRP and 90°-CFRP are cracking of the resin matrix and debonding at the fiber/matrix interface, but carbon fiber is hardly damaged. Therefore, the mechanical properties of 0°-CFRP laminates are superior to those of 45°-CFRP and 90°-CFRP laminates. This anisotropy brings different failure modes at the onset of failure process to CFRP composite sandwiches: brittle fracture occurred in 45°-CFRP skin and 90°-CFRP skin,
but not occurred in 0°-CFRP skin, due to different fiber directions of the CFRP skin. As a consequence, the 0°-CFRP/PMSF composite sandwiches have the most excellent flexural properties compared with 45°-CFRP/PMSF composite sandwiches and 90°-CFRP/PMSF composite sandwiches. This study provided a new core material for the application of CFRP composite sandwiches.

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Data availability statement

No new data were created or analysed in this study.

Author contributions

Writing–original draft, Resources, J A Liu; Writing–editing, Investigation, Z Q Dong; Resources, X Y Zhu; Methodology, Data curation, Validation, W B Sun; Investigation, Z Q Huang. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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