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Impact Properties of Three-Dimensional Orthogonal Woven Composites with Ramie/Glass Fiber Grid Hybridization

RESEARCH ARTICLE

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ABSTRACT

To enhance the damage tolerance of ramie fiber reinforced composites, a novel three-dimensional (3D) orthogonal structure with graded ramie/glass fiber hybridization (warp/weft gradient hybridization, Z-direction glass fiber reinforcement) was proposed. After the 3D orthogonal woven fabrics as preforms woven by a self-built 3D woven loom, the composites penetrated by epoxy resin were fabricated via vacuum-assisted resin transfer molding (VARTM). In this work, the impact properties of three-dimensional orthogonal woven composites with ramie/glass fiber grid hybridization were investigated. Compared to pure glass fiber reinforced three-dimensional orthogonal composites and traditional laminates, the grid hybrid composites showed highest peak force and smallest damage area under 15 J impact. Furthermore, the post-impact residual strength of grid hybrid composites showed highest strength retention rate (over 90%), indicating its superior ability to preserve load-bearing capacity after impact. Notably, the GH-3DOWC demonstrated superior damage tolerance, reducing the damage area by 61.5% and maintaining a compressive strength retention rate of over 90% under 15 J impact. This study demonstrated the advantages of the grid hybrid 3D composites reinforced by ramie and glass fibers, providing new insights for developing low-cost, high-damage-tolerance green engineering materials.

1. Introduction

Three-dimensional orthogonal woven fabric (3DOWF), characterized by its unique interlocking structure with Z-direction yarns along the thickness, significantly mitigates the weaknesses of traditional laminated composites such as weak interlaminar performance and susceptibility to delamination (Boroomand et al.,2023; Hu et al, 2020; Zhao et al. , 2024). This structure enables the Z-direction fibers to effectively bridge cracks and suppress damage propagation when the composite is subjected to impact or shear loads. It has found widespread applications in high-strength and high-reliability fields including aerospace (engine nacelles, radomes), wind power (shear webs for blades), and transportation (lightweight crash-resistant structures). Compared to two-dimensional laminates, the 3D orthogonal structure demonstrates revolutionary potential in damage tolerance, particularly in suppressing barely visible impact damage (BVID) caused by low-velocity impacts (e.g., tool drop, bird strike) (Bulut & Erkliğ, 2017; Kim & Park, 2021; Umair et al., 2022).

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To further optimize performance and cost, researchers have attempted to hybridize high-performance synthetic fibers (e.g., glass, carbon fibers) with natural fibers (e.g., flax, bamboo) to create 3DOWF. However, current researches face two key challenges: a lack of studies on dynamic impact performance and oversimplified hybrid structural designs. Existing literatures primarily focuses on static mechanical properties (tensile, flexural) or quasi-static interlaminar shear strength (ILSS) (Niu et al., 2025; Ramakrishnan, Ramnath, Elanchezhian, Kumar, & Gowtham, 2018), with insufficient attention paid to low-velocity impact behavior. Furthermore, most current studies adopt uniform hybridization, where different fibers are evenly distributed within the fabric (Fazeli, Kern, Hoffmann, & Cherif, 2015; Singh, Singh, & Gill, 2018; Wang et al., 2017). This design struggles to reconcile conflicting requirements: high-modulus fibers (e.g., glass) need to bear the primary load, while high-toughness fibers (e.g., flax) should maximize energy absorption (Kuang et al., 2018; M. Li, Wang, Boussu, & Soulat, 2020; Wang et al., 2017).

The incorporation of natural fibers contributes not only to reduced density and cost, but also enhances toughness, damping, and energy absorption. For instance, flax/glass hybrids improve post-impact residual strength in laminates, while bamboo/carbon systems enhance damage tolerance without compromising stiffness. Nevertheless, prevailing research predominantly focuses on uniform hybridization, wherein fibers are distributed evenly or randomly throughout the composite. Although such configurations offer certain performance trade-offs, they often fail to achieve optimal functional synergy between high-stiffness and high-toughness fibers under impact loading.

By contrast, gradient or non-uniform hybridization allows for tailored performance through controlled variations in fiber type, content, and arrangement along the thickness direction. This approach promotes more regulated and progressive damage propagation, thereby improving damage tolerance and energy absorption efficiency. However, existing studies on gradient hybridization remain largely confined to conventional laminates and quasi-static conditions, leaving the underlying mechanisms in three-dimensional orthogonal woven composites under dynamic impact insufficiently explored.

Furthermore, low-velocity impact testing is of paramount importance for evaluating the mechanical properties of composite materials. Such testing not only serves as a fundamental method for assessing a composite's resistance to external accidental loads, but also constitutes a crucial experimental step for revealing the mechanism by which three-dimensional integral structures suppress delamination, and for verifying the effectiveness of gradient hybrid designs in enhancing impact energy dissipation and damage tolerance.

Inspired by the concept of non-uniform hybridization, this paper designs and fabricates a grid hybrid three-dimensional orthogonal woven fabric (GH-3DOWF) based on hybrid 3DOWF, and prepares grid hybrid three-dimensional orthogonal woven composite (GH-3DOWC) using VARTM. The study focuses on their mechanical properties and failure modes under low-velocity impact.

Additionally, all glass plain-woven composite (AG-PWC) and all-glass 3D orthogonal woven composites (AG-3DOWC) are fabricated for comparison, to investigate the influence of different structures and materials on their low-velocity impact performance. This experiment employed the method of mean and standard deviation for standardisation.

2. Structure design and experiment method

2.1 Raw materials

The GH-3DOWF was produced using E-glass fibers (model EDR13-300-386, supplied by China Ju shi Co., Ltd.) and 9-ply ramie yarns (provided by Shanghai Zhang dan Garment Accessories Co., Ltd.). The resin matrix system consisted of bisphenol-A epoxy resin (model JL-235, epoxy value 0.56 mol/100g) and hardener (model JH-242), both produced by Hangmo Jiafa New Materials (Suzhou) Co., Ltd.

2.2 Structure design

Fig.1 illustrates the structural schematic of the GH-3DOWF. The glass fiber content progressively decreases from 100% at the top layer to 0% at the core layer (e.g., the second layer achieves 67% glass fiber content through alternating arrangements of two glass fibers and one ramie yarn per pattern repeat), then symmetrically increases toward the bottom layer, creating a grid hybridization. Z-direction yarns, exclusively glass fibers, interlace to bind the warp and weft yarns, thereby enhancing delamination resistance. Table 1 summarizes the detailed weaving parameters of the GH-3DOWF.

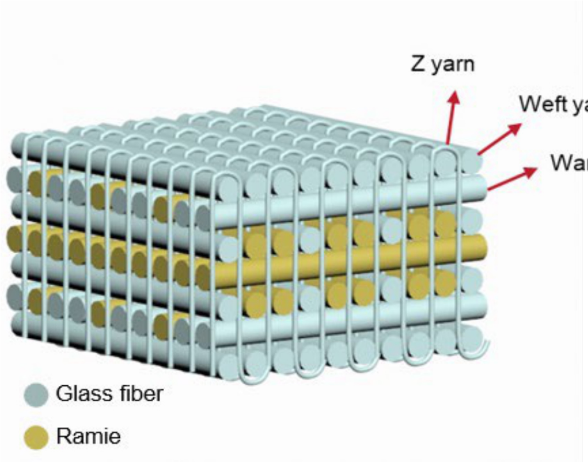


Figure 1. Structural schematic of the GH-3DOWF

Table 1. Specific weaving parameters of GH-3DOWF

Name	First Layer	Second Layer	Third layer	Forth layer	Fifth layer	Sixth layer	Seventh layer
AG-3DOWF	G	G	G	G	G	G	G
GH-3DOWF	G	G/R (67:33)	G/R (33:67)	R	G /R (33:67)	G /R (67:33)	G

2.3 Fabrication and molding of 3DOWF

The weaving process of the 3DOWF is illustrated in Fig.2. The warp yarns and Z-yarns also called pillar yarns are drawn from the creel, pass through the reed, and interlace/bind with the weft yarns by controlling the movement of the heddle frames, forming an integrated three-dimensional textile structure.The GH-3DOWC were fabricated using VARTM, with the specific molding process illustrated in Fig.3. Pre-cure at 50°C for 3 hours, then heat to 70°C for a further 7 hours to complete curing.Detailed composite material parameters as the Table 2.

Table 2. Composite Material Parametes

Name	Fiber volume fraction	Density	Thickness
GH-3DOWC	48%	1.45g/cm^3	5.43mm
AG-3DOWC	45%	1.88g/cm^3	4.32mm
AG-PWC	52%	1.92g/cm^3	4.53mm

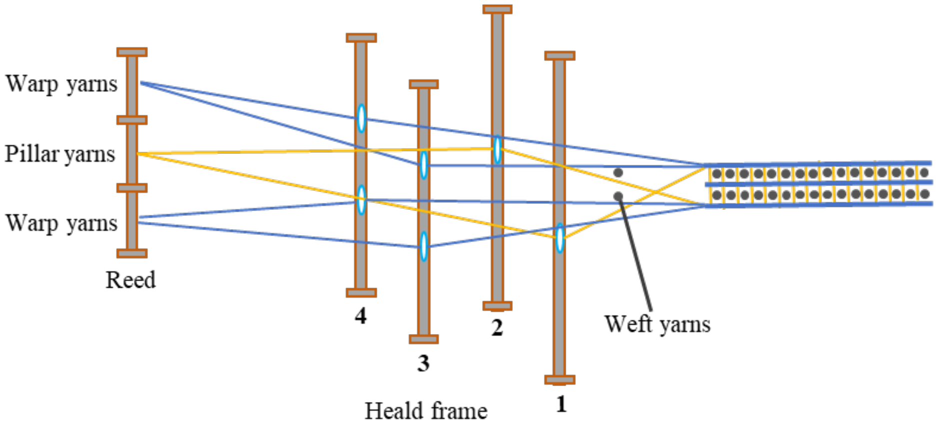


Figure 2. Weaving Process of 3DOWF

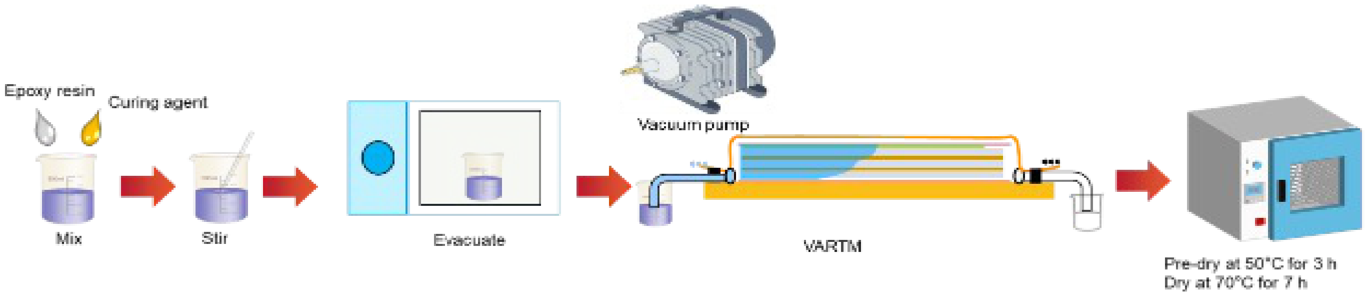


Figure 3. Process schematic of for VARTM

2.4 Low-velocity impact testing

Low-velocity impact tests were conducted on a drop-weight impact tester (Xusai) in accordance with ASTM D7136/D7136M (Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event). Specimen dimensions were 100 mm × 100 mm, with three parallel samples tested per group.

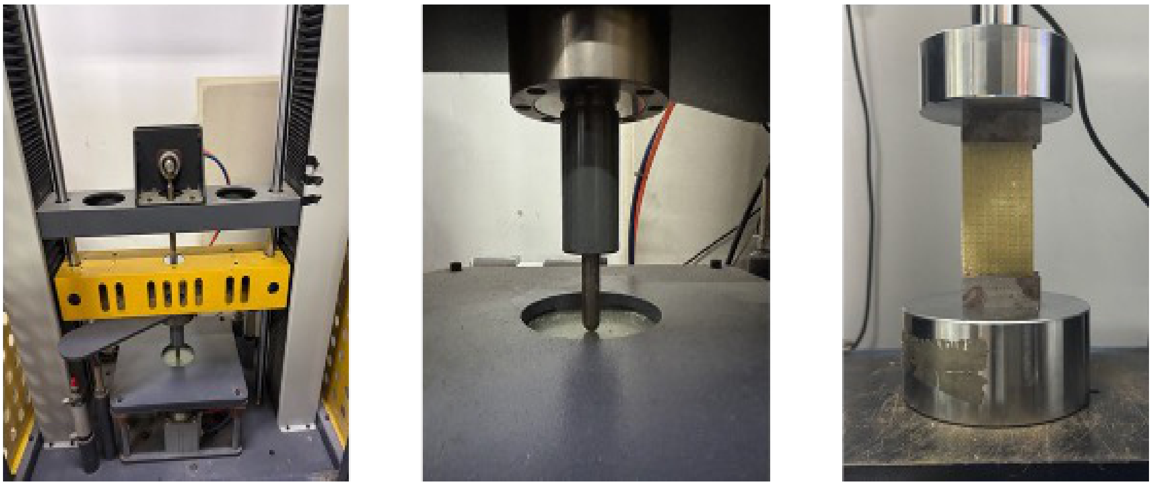
2.5 Post-impact residual strength testing

The post-impact residual strength was determined by measuring the transverse compressive strength of the impacted specimens. Tests were performed on a universal testing machine (INSTRON, Model 5967) in accordance with ISO 14126 and ASTM D7137/D7137M (Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates). For comparison with the pre-impact compressive strength, the impacted specimens were trimmed to dimensions of 100 mm × 58 mm. A constant loading rate of 2 mm/min was applied, with three parallel specimens tested per group. The instrumentation and testing methodology are presented in Fig.4.

3. Results and analysis

3.1 Contact force-time curves of the impact test

Fig.5 shows the fabricated GH-3DOWC sample and its cross-sectional views. The ramie fiber and glass fiber showed good interface adhesion in GH-3DOWC. Fig.6 presents the force-time curves of materials under 15J low-velocity impact. As shown in picture, the curve of AG-3DOWC is characterized by the highest peak force (approximately 3700 N), yet it is followed by a sharp decline, indicating that the material primarily resists impact through high stiffness and undergoes catastrophic failure



(a) (b) (c)

Figure 4. (a) Low-velocity impact instrument, (b) Impact process, (c) The process of post-impact residual strength testing

due to brittle fracture. In contrast, the AG-PWC displays the gentlest curve with a lower peak force (approximately 3300 N) and a broad force plateau. The GH-3DOWC exhibits a curve intermediate between the other two, with the lowest peak force (approximately 3000 N) but a more gradual post-peak decay, demonstrating superior toughness. This reflects the synergistic effect of ramie fibers and the three-dimensional gradient structure, facilitating a multi-stage energy absorption process involving mechanisms from fiber fracture to pull-out, thereby enhancing the material's damage tolerance and energy absorption efficiency.

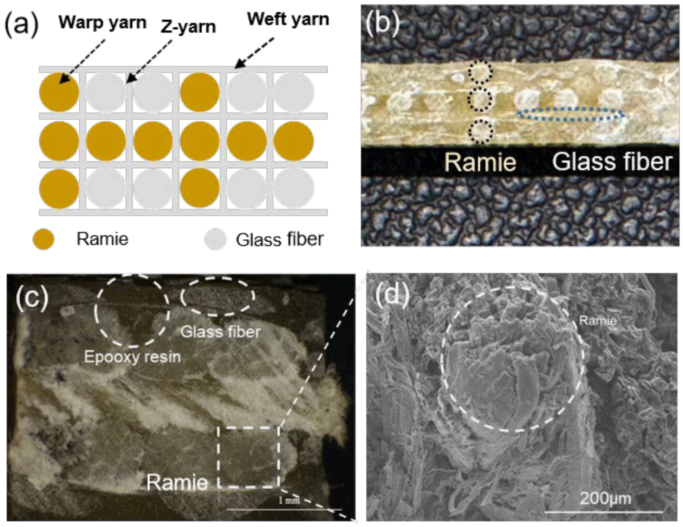


Figure 5. GH-3DOWC: (a) Schematic diagram and (b) Picture of Warp-direction view , (c) Amplified picture and (d) its SEM image of cross-sectional view

3.2 Analysis of impact damage morphology

Fig.7 show the surface damage morphology of the GH-3DOWC, the AG-3DOWC, and the AG-PWC after 15 J impact tests. The 15 J impact led to increased damage severity and larger surface damage areas in all three composite materials.

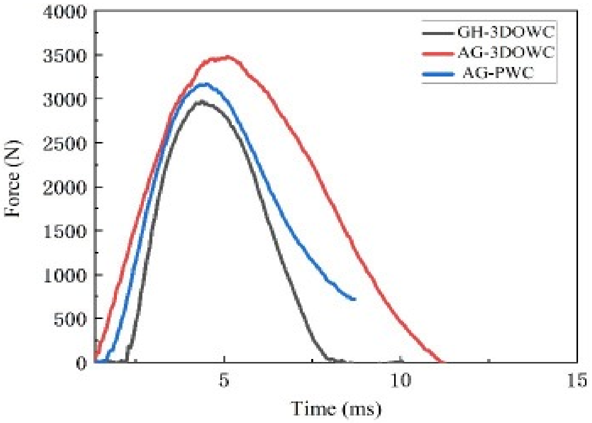


Figure 6. Impact contact force-time curves of composites under 15J impact energy

The GH-3DOWC exhibited enlarged resin whitening zones on the upper surface. Similarly, both the AG-3DOWC and the AG-PWC showed expanded resin whitening areas, with the latter also developing a deeper impact-induced depression. When comparing the PW-GFL, the AG-3DOWC, and the ramie-integrated GH-3DOWF, a clear reduction in both the extent of damage and the affected surface area was observed.

The damage area on the upper surface was quantified using Image-J analysis software. As shown in the magnified views of the damaged regions, the GH-3DOWC exhibited significantly less damage compared to the other two materials. Both the AG-3DOWC and the AG-PWC showed extensive surface resin damage, with measured damage areas of 45.273 mm² and 61.129 mm² under 15 J impact, respectively. In contrast, the GH-3DOWC displayed only minor surface resin damage at 15 J. None of the three composite types experienced full penetration of the upper surface, though they exhibited varying degrees of surface damage. The lower surface of the grid hybrid composite showed slight resin damage, while the other two materials displayed more pronounced damage traces.

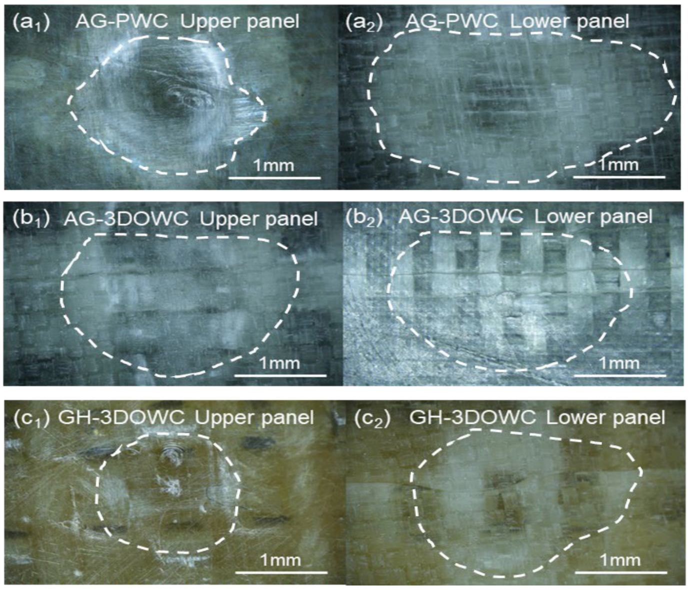


Figure 7. Panel damage morphology: (a$_1$) AG-PWC Upper panel, (a$_2$) PW-GFL Lower panel, (b$_1$) AG-3DOWC Upper panel, (b$_2$) AG-3DOWC Lower panel, (c$_1$) GH-3DOWC Upper panel (c$_2$) GH-3DOWC Lower panel

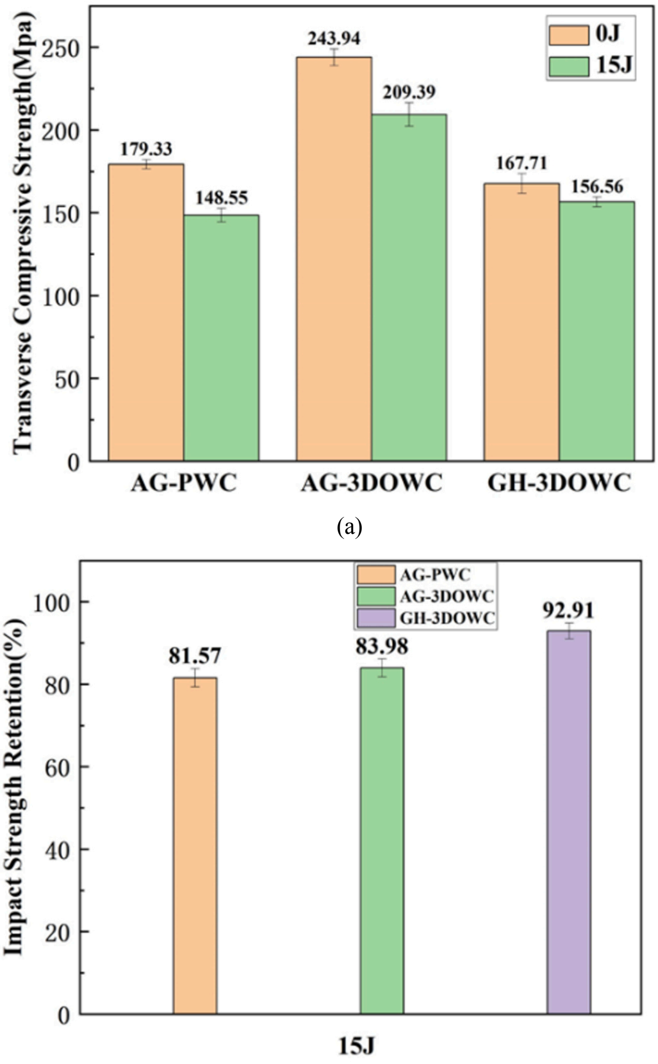
3.3 Post-impact residual strength

Fig.8 presents the post-impact residual strength test results of the composites. Fig.8 (a) compares the transverse compressive strength after 15 J impacts with the original (pre-impact) transverse compressive strength for the GH-3DOWC, the AG-3DOWC, and the AG-PWC. Fig.8 (b) shows the corresponding compressive strength retention rates after impact at these energy levels. As observed in the figure, all composites exhibited a noticeable decrease in transverse compressive strength due to impact damage. Furthermore, the extent of strength reduction increased with higher impact energy, leading to a corresponding decline in the strength retention rate. Owing to its minimized damage during impact, the GH-3DOWC demonstrated a significantly higher retention of transverse compressive strength compared to the AG-3DOWC and the AG-PWC. Its strength retention reached 95.54% after the 15 J impact—far exceeding the values of the other two composites. In contrast, the plain-woven glass fiber laminate exhibited severe damage on both the upper and lower panels after the 15 J impact, resulting in a strength retention of only 81.57%.

4. Conclusions

In this work, a grid hybrid three-dimensional orthogonal woven composite (GH-3DOWC) reinforced by ramie and glass fiber were designed and fabricated. Then the mechanical performance under low-velocity impact as well as their post-impact residual strength were investigated. The main conclusions are as follows:

The 3D orthogonal woven structure showed significantly improved impact resistance compared to traditional laminates.



(a)

(b)

Figure 8. Post-impact residual strength of composites: (a) Lateral compressive strength before and after impact, (b) Strength retention

The GH-3DOWC showed higher peak force under 15 J impact, attributed to the synergistic effect of its 3D orthogonal architecture and grid glass/ramie hybrid design on overall rigidity. The lower peak of the GH-3DOWC indicates a softer initial response.The Z-yarn reinforcement also endowed the AG-3DOWC with superior stiffness over the AG-PWC.The post-peak force decay reveals the damage evolution.

Compared with AG-3DOWC the damage area of GH-3DOWC was reduced by 25.9% under 15 J impact. Furthermore, the grid hybrid 3DOWF incorporating ramie fibers demonstrated even greater improvement, reducing the damage area by 61.5% compared to conventional laminates. The residual strength of both the AG-3DOWC and the AG-PWC fell below 85% strength retention under 15 J impact, while the GH-3DOWC maintained over 90% strength retention, indicating its superior ability to preserve load-bearing capacity after impact. The fibrillation fracture of hemp fibres in the SEM image resulted in lower peaks and reduced damage area for GH-3DOWC.

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