# Interlaminar Shear Properties of Multilayer Interconnected Carbon Fiber Weft-Knitted Biaxial Laid-in Yarn Fabric Reinforced Composites Postprint

**Authors:** Xiaoyuan Pei, Shang Bo, Li Jialu, Chen Li, Ding Gang

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## Abstract

The interlaminar shear properties of carbon fiber weft-knitted biaxial multilayer weft-inserted fabric reinforced composites with three-layer, four-layer, and five-layer connections were investigated in the 0° and 90° directions. The results indicate that the interlaminar shear strength increases with increasing fiber volume content. The interlaminar shear load-deflection curves of the composites exhibit a tendency toward linear variation, with an abrupt load drop after reaching the maximum value, demonstrating characteristics of brittle fracture. Analysis of the fracture morphology of interlaminar shear test specimens reveals that the reinforcement structure exerts a significant influence on the interlaminar shear performance of the composites. The shear failure mode of the specimens is delamination failure, with numerous cracks generated between fabric layer groups.

## Full Text

## Abstract

This study investigates the interlaminar shear properties of carbon fiber-reinforced composites with multilayer-connected biaxial weft knitted (MBWK) fabrics along 0° and 90° directions. Three types of reinforcement structures were examined: three-layer-connected, four-layer-connected, and five-layer-connected MBWK fabrics. The results demonstrate that interlaminar shear strength increases with fiber volume fraction. The load-deflection curves exhibit predominantly linear behavior up to maximum load, followed by sudden load drop, characteristic of brittle fracture. Fracture surface analysis reveals that reinforcement structure significantly influences interlaminar shear performance, with shear failure occurring primarily through delamination and extensive cracking at interfaces between fabric groups.

**Keywords:** composites, multilayer-connected biaxial weft knitted fabric, polymer matrix composites, shear properties, failure mechanism

## 1. Introduction

Multilayer-connected biaxial weft knitted (MBWK) fabric is a specialized non-crimp fabric based on a 1$×$1 rib knit structure. In MBWK fabrics, the inserted warp and weft yarns remain perfectly parallel and straight, enabling full utilization of high-performance fibers' high strength and modulus while leveraging the deformability of knitted loops. This combination yields not only excellent mechanical properties but also superior three-dimensional formability compared to other textile structures [?]. Additionally, MBWK fabric-reinforced composites offer strong load-bearing capacity, low cost, and short production cycles, making them highly attractive for high-performance composite applications. These materials are widely used in manufacturing pilot helmets, automotive hoods, and body panels, where the reinforcement structure parameters determine and influence all performance characteristics.

Previous research has established foundational understanding of these materials. H. Kong et al. [?] investigated the deformation resistance and mechanisms of warp-knitted biaxial and triaxial fabrics under off-axis loading, finding that stitch density, yarn tension, and position significantly affect off-axis deformability. Li et al. [?] developed a fiber bundle element model for integral forming of MBWK fabrics comprising geometric, microscale, and numerical sub-models, with results validated against experimental data. Dexter et al. [?] evaluated the performance of multiaxial warp-knitted/stitched fabric-reinforced composites through tensile and open-hole tensile tests, concluding that multiaxial warp-knitted fabrics are suitable for manufacturing high-quality aerospace composites. Sun et al. [?] conducted compression tests on multiaxial multilayer warp-knitted fabric-reinforced composites under quasi-static and high-strain-rate loading, revealing that compressive stiffness, stress, and strain are sensitive to strain rate variations. Kang et al. [?] studied the energy absorption characteristics of aramid warp-knitted fabric-reinforced composites using energy methods, demonstrating that warp-knitted axial fabric-reinforced composites exhibit higher flexural properties than woven fabric-reinforced composites.

While biaxial multilayer-inserted yarn fabric composites exhibit high tensile, compressive, and flexural strengths, their interlaminar shear strength is relatively low. Determining interlaminar shear strength is essential for safe component design. Current research on interlaminar shear properties of multiaxial warp-knitted fabric-reinforced composites remains limited. Li et al. [?] tested the interlaminar shear properties of biaxial warp-knitted T700/bismaleimide (BMI) 6421 composites and compared them with unidirectional T700/BMI6421 composites. Han et al. [?] investigated the interlaminar shear properties of biaxial (+45°/-45°) carbon fiber warp-knitted fabrics from German Liba and Karl Mayer companies, testing mechanical properties in 0°, 90°, and 45° directions.

Analysis of variance (ANOVA) is a multivariate statistical method widely used for composite performance analysis. Qi et al. [?] employed single-factor ANOVA to study the relationship between tensile strength and fiber volume fraction in carbon fiber MBWK fabric-reinforced composites. Song et al. [?] used two-factor ANOVA to investigate thermal effects of accelerated aging on the tensile strength of three-dimensional braided epoxy composites. Fan et al. [?] studied the thermal aging performance of carbon fiber epoxy composites and developed two statistical models to predict residual flexural strength and service life.

Laminated composites exhibit high tensile, compressive, and flexural strengths but typically low interlaminar shear strength because the interlaminar shear strength of fiber-reinforced composites depends on interface and matrix strength. In MBWK fabric-reinforced composites, the inclusion of binding yarns significantly improves interlaminar performance. This paper analyzes the interlaminar shear properties of MBWK fabric-reinforced composites. Based on experimental results, two-factor ANOVA is applied to examine the relationship between carbon fiber volume fraction and shear strength. Additionally, the effect of different connection layer numbers on shear performance is investigated, and compression failure mechanisms are summarized based on fracture morphology observations.

## 2. Experimental

### 2.1 Materials and Fabrication

The reinforcement structures consisted of three-layer-connected, four-layer-connected, and five-layer-connected biaxial weft knitted fabrics, as shown in [Figure 1: see original paper]. The three-layer-connected MBWK fabric comprises two surface layers of carbon fiber weft yarns and one middle layer of inserted warp yarns, with black lines representing carbon fiber bundles in both weft and warp directions. The weft and warp carbon fiber bundles maintain a 90° angle without interlacing, held together by white polyester stitching loops in a 1$×$1 rib structure. Fabric thickness is approximately 1 mm.

The four-layer-connected MBWK fabric features a different architecture but uses identical yarns. The first and fourth layers consist of weft carbon fiber bundles, while the second and third layers contain warp carbon fiber bundles. No distinct boundary exists between the second and third warp layers; these two layers of warp carbon fiber bundles are consolidated into combined warp bundles within the same plane. Fabric thickness is approximately 1.25 mm. The five-layer-connected MBWK fabric has weft carbon fiber bundles in the first, second, fourth, and fifth layers, with warp carbon fiber bundles in the third layer. Since polyester stitching yarn mass does not affect composite quality, only carbon fiber volume fraction is calculated.

Carbon fiber volume fraction ($V_f$) is calculated based on MBWK fabric mass and actual dimensions of cured composite laminates using the formula:

$$V_f = \frac{m_f}{V_c \times r_f}$$

where $V_f$ is carbon fiber volume fraction, $m_f$ is carbon fiber mass in the composite (g), $V_c$ is total composite volume (cm$^3$), and $r_f$ is T300 carbon fiber density (g/cm$^3$).

Each connection configuration is designated as a "fabric group." To achieve a target composite thickness of 4 mm and varying fiber volume fractions, multiple identical fabric groups were stacked in specific sequences. MBWK fabrics and epoxy resin were then consolidated using resin transfer molding (RTM). lists the stacking sequences and average fiber volume fractions for different MBWK fabric composite groups.

In , specimens 1#, 2#, and 3# use three-layer-connected MBWK fabrics with 4, 5, and 6 stacked groups, respectively. Specimens 4#, 5#, and 6# use four-layer-connected MBWK fabrics with 3, 4, and 5 stacked groups. Specimens 7#, 8#, and 9# use five-layer-connected MBWK fabrics with 2, 3, and 4 stacked groups.

The matrix material is TDE-86 epoxy resin (4,5-epoxycyclohexane-1,2-dicarboxylic acid diglycidyl ester) with an epoxy value of 0.90$±$0.02. The curing agent and catalyst are 70# anhydride and aniline, respectively. During curing, the mold was placed in an oven, resin was injected under 0.2–0.3 MPa pressure to fully impregnate the fiber preform, and the composite was cured at specified temperatures and times listed in .

## 2.2 Testing Methods

Interlaminar shear testing followed ASTM D2344/D2344M (Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates) [?] using a universal testing machine at a loading rate of 1.0 mm/min. Specimen dimensions were 24 mm × 8 mm × 4 mm. For MBWK fabric-reinforced composites, the 0° direction was defined along the weft carbon fiber direction, and the 90° direction along the warp carbon fiber direction. Five specimens were tested for each condition, with results averaged. Interlaminar shear strength ($F_{sbs}$) was calculated as:

$$F_{sbs} = \frac{3P}{4bh}$$

where $F_{sbs}$ is interlaminar shear strength (MPa), $P$ is failure or maximum load (N), $b$ is specimen width (mm), and $h$ is specimen thickness (mm).

## 3. Results and Discussion

### 3.1 Effect of Fiber Volume Fraction on Interlaminar Shear Properties

The study employed MBWK fabrics with different connection layers. Since specimens exhibited similar load-deflection behavior, only three-layer-connected specimens are analyzed in detail. [Figure 2: see original paper] presents load-deflection curves for specimens 1#, 2#, and 3# along 0° and 90° directions.

The curves show linear characteristics from initial loading to maximum load, indicating good fiber-matrix bonding with both components sharing the compressive load. After reaching maximum load, the curves drop abruptly, demonstrating brittle fracture behavior. No audible sounds were detected during testing until sudden, loud resin cracking and fiber breakage occurred at final failure. This behavior arises from different stress transfer mechanisms in fibers and resin under shear loading. Shear forces disperse through fibers, forcing fiber-matrix debonding while stresses in individual fibers gradually attenuate. Under constant loading rate, debonded fibers fracture due to overloading. Failure is characterized by brittle fracture caused by fiber bundle breakage, with slight curve irregularities reflecting progressive damage accumulation.

Shear property parameters for MBWK fabric-reinforced composites with different fiber volume fractions and connection layers are summarized in . When the number of fabric groups is even (four-layer connection), specimens exhibit identical carbon fiber volume fractions in 0° and 90° directions, yielding similar test results. With odd numbers of fabric groups (three- and five-layer connections), different numbers of carbon fiber layers in 0° and 90° directions result in higher fiber volume fraction in the 0° direction and correspondingly superior shear properties compared to the 90° direction.

Interlaminar shear strength of MBWK fabric-reinforced composites depends on matrix and interface strengths. During shear testing along 0° or 90° directions, loads are primarily borne by the epoxy matrix and interface, which transfer shear stresses to carbon fibers for gradual dispersion. Failure occurs when shear stresses exceed the composite's capacity. [Figure 3: see original paper] illustrates the relationship between fiber volume fraction and shear strength, showing that shear performance improves with increasing fiber volume fraction within the studied range. Higher carbon fiber volume fraction enables more uniform stress distribution and greater shear resistance.

### 3.2 Effect of Reinforcement Structure

Three reinforcement structures were investigated: three-layer-connected, four-layer-connected, and five-layer-connected MBWK fabrics. To isolate structural effects, shear strength data at identical fiber volume fractions were compared through linear fitting of experimental results, as shown in [Figure 4: see original paper]. Correlation coefficients for the fitting curves are presented in , with all $R^2$ values very close to 1. Significance testing confirms strong linear relationships between shear strength and carbon fiber volume fraction along both 0° and 90° directions, though this correlation is limited to the studied fiber volume fraction range.

[Figure 4: see original paper] reveals that at lower fiber volume fractions, five-layer-connected composites exhibit the highest interlaminar shear strength, while three-layer-connected composites show the lowest. However, at higher fiber volume fractions, three-layer-connected composites surpass five-layer-connected composites in shear strength. This behavior is attributed to the binding yarns, which bind fabric layers and transfer loads. Within each fabric group, layers are tightly bound by pre-tensioned stitching yarns, creating a structurally integrated unit with reduced interlayer resin thickness. [Figure 5: see original paper] shows a longitudinal cross-section of MBWK fabric-reinforced composites, where minimal resin regions are visible only between adjacent fabric groups, indicating that binding yarns enhance intragroup interlaminar performance. Consequently, interfaces between fabric groups become the composite’ s weak layers.

The ratio of fabric layers to fabric groups significantly influences shear performance. At low fiber volume fractions, three-layer-connected composites (12 total layers, 11 interfaces; 4 groups, 3 group interfaces) have a group-to-total interface ratio of 3:11 = 0.272. Five-layer-connected composites (10 total layers, 9 interfaces; 2 groups, 1 group interface) have a ratio of 1:9 = 0.111. Since binding yarns strengthen intragroup interfaces while intergroup interfaces remain relatively weak, the lower intergroup ratio in five-layer-connected composites (0.111) results in higher shear strength than three-layer-connected composites (0.272) at low fiber volume fractions.

At high fiber volume fractions, three-layer-connected composites (18 layers, 17 interfaces; 6 groups, 5 group interfaces) have a ratio of 5:17 = 0.294. Five-layer-connected composites (20 layers, 19 interfaces; 4 groups, 3 group interfaces) have a ratio of 3:19 = 0.158. The intergroup ratio for five-layer-connected composites increases to 1.423 times its low-volume-fraction value, while the three-layer-connected ratio increases only 1.080 times. Thus, at high fiber volume fractions, three-layer-connected composites approach or exceed the shear strength of five-layer-connected composites.

### 3.3 Fracture Morphology Analysis

[Figure 6: see original paper] shows typical interlaminar shear fracture in a five-layer-connected MBWK fabric-reinforced composite with two fabric groups, where red and blue lines each represent one fabric group. Although cracks initiate within fabric groups, primary cracks predominantly occur between fabric groups. [Figure 7: see original paper] displays fracture patterns for three-layer-connected composites with 4, 5, and 6 fabric groups, respectively, again showing major cracks at intergroup regions.

Binding yarns improve intragroup interlaminar performance, making intergroup interfaces the composite’ s weak link. As shear stress increases, intergroup interfaces fail first, generating primary cracks between fabric groups. Even when intragroup cracks occur, binding yarns require additional energy for delamination, thereby improving interlaminar strength. The polyester binding yarns stretch during relative slip of delaminated layers, absorbing energy and enhancing delamination toughness. With further crack propagation, increased tensile deformation causes debonding between binding yarns and the matrix, followed by yarn pull-out and fracture. This sequence of stretching, debonding, pull-out, and fracture consumes substantial energy, improving shear strength. However, the use of polyester rather than high-performance fibers limits the magnitude of interlaminar shear strength enhancement.

### 3.4 Two-Factor ANOVA

Two-factor ANOVA was performed to determine statistical relationships between influencing factors (fiber volume fraction and reinforcement structure) and interlaminar shear strength along 0° and 90° directions. Results are presented in and using Type III sum of squares analysis. The adjusted $R^2$ values of 0.838 for the 0° direction and 0.903 for the 90° direction indicate good model fit.

ANOVA results show highly significant models, with F-statistics of 29.542 and 52.404 for 0° and 90° directions, respectively. The P-values for both fiber volume fraction and connection layer number are 0.000 (<0.05), indicating significant effects on shear strength at $\alpha = 0.05$ significance level. As shown in [Figure 3: see original paper], shear strength increases with fiber volume fraction, with three-layer-connected composites showing the greatest strength increase and five-layer-connected composites the smallest. Reinforcement structure thus significantly influences MBWK fabric-reinforced composite shear strength.

## 4. Conclusions

Carbon fiber volume fraction substantially affects the interlaminar shear properties of MBWK fabric-reinforced composites. Within the experimental range, interlaminar shear strength exhibits excellent linear correlation with carbon fiber volume fraction. Reinforcement structure also significantly influences composite interlaminar shear performance. The primary shear failure mode is delamination, with cracks predominantly occurring between fabric groups. Binding yarns provide moderate improvement in interlaminar strength.

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