Estimation of interlaminar shear strength in glass epoxy composites by experimental and finite element method

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Abstract. The objective of the present work is to estimate interlaminar shear strength in glass epoxy composite by experimental and finite element method. A woven glass fabric (0°- 90°) and epoxy are used in the preparation of the composite. Interlaminar shear strength (ILSS) is estimated experimentally by ASTM D 2344 and ASTM C 1425 for thin and thick laminates. While adopting the procedure mentioned in ASTM D 2344, the sample dimensions of thin and thick laminate are 32 X 10 X 2 mm^3 and 80 X 10 X 10 mm^3 respectively. Three-point bend test is conducted on Universal testing machine made by United Calibration Corporation with model No. STM 50 kN at a loading rate of 1.5 mm/minute. For the standard ASTM C 1425, the sample dimensions of thin and thick laminate are 30 X 15 X 2 mm^3 and 30 X 15 X 10 mm^3 respectively. The fixture is fabricated for both thick and thin laminate for estimating interlaminar shear strength. The obtained experimental results are compared with interlaminar shear strength estimated in ANSYS, and the correctness of finite element analysis is verified. The results interpreted in the present work are also compared with the published results available in the literature, and it is noticed that the deviation is agreeable. From the available literature, it is also suggested that ASTM C 1425 is recommended over the other methods since the sustainability of the material is achieved while examining the interlaminar shear strength.

1. Introduction and Literature Review

Laminated fibre reinforced polymer matrix composite materials find successful applications in the field of aerospace, automobile, marine, military, etc., because of their directional strength and stiffness. Manufacturing methods of producing composites limit the fibres in the thickness direction to uphold the transverse load which affects the ILSS property of the composites [1]. The interlaminar shear stresses may be caused due to different reasons, one of which is the material property between the layers and out-of-plane stress \(\sigma_z, \tau_{xz}, \tau_{yz}\) defined at the interface between layers in a laminated composite material [2]. The interlaminar shear stresses play important role in the failure strength of composite laminate [3]. It can shear apart the interface in the corresponding directions.

ZhihangFanMichael et al,[4] examined the distribution of interlaminar shear strength (ILSS) in neat resin and CNT reinforced epoxy resin. The results showed that the introduction of MWCNT into the composite increased the ILSS by 33%. Mahesh Chandrashekhar Swamy et al [5] examined the influence of fibre orientation on ILSS properties of bidirectional laminated glass fiber specimens. The specimens were subjected to bending loads causing shear stress in the structures. The result show that for same thickness, unidirectional glass/epoxy composite laminates have more shear strength over other types of laminates. Mauro Henrique Lapena et al [6] discussed the mechanical properties of Glass epoxy tubes manufactured by filament winding and its ILSS was 36MPa.

Khalil M. Elawadly et al [7] proved that the first ply failure occurs at the neutral axis of the specimen. Interlaminar shear stress is maximum along the neutral axis and failure occurs through the resin or at the interface of resin and fiber. Here, the fibers do not fail. Surendra Kumar M et al [8],
experimentally investigated mechanical behavior of glass/epoxy composites at cryogenic temperatures. Laminates of woven and chopped E-glass fibers of 50% weight fraction were reinforced with epoxy matrix. Three point bending test was carried out to find interlaminar fracture behavior at cryogenic and ambient conditions. The ILSS values for chopped fiber composites are found to be lower than woven fiber composites due to less effective bonding with the matrix per unit surface area of the fibers. The higher ILSS values for cryogenically conditioned samples are attributed to enhance mechanical keying factor by the generation of cryogenic compressive stresses. This increases the friction at the interface due to contraction of the epoxy matrix at low temperature. The composite laminate needs an optimum time to transfer load effectively through the interface. Kishore Kumar et al [10] altered the CNT reinforced epoxy resin by weight and noticed that the tensile strength is 242.22 MPa and its flexural strength is 332.53 MPa. K Chandrasekhar et al [11] characterized hybrid composite to estimate ILSS by short beam shear test. In the longitudinal direction, the average interlaminar shear strength was observed to be 56±9 MPa.

In the present work, the interlaminar shear strength is estimated by experimental and finite element methods for thick and thin laminates whose sample size is mentioned in table 1.

2. Methodology

In the present work, interlaminar shear strength is estimated by experimental method and finite element analysis by ANSYS. Section 2.1 describes the details of experimental work carried out for thin and thick laminates as per ASTM D 2344. In the heading 2.2, the details of finite element analysis are presented. Section 2.3 elaborates the necessity for fixture and the procedure to find out interlaminar shear strength while adopting ASTM C 1425 for thin and thick laminates. The elastic constants are estimated by extended simple rule of mixtures [9] and are used in the preprocessor module of ANSYS. Shell element is used to generate the finite element model. Boundary conditions are applied as per the standards and interlaminar shear strength is estimated. Under the heading 3.1 and 3.2, results and discussions are elaborated in detail.

2.1 Experimental set up for three point bend specimen

Hand layup process is used to fabricate glass epoxy samples. Woven fabric and epoxy resin are selected to prepare the composite. All the experimental work was carried out at Ceramic Matrix Composite Division, Directorate of High Temperature Carbon-Carbon Composite, Advanced System Laboratory (ASL), Hyderabad. Woven fabric with (0° - 90°) was used. For E-glass epoxy, 6 layers were used for thin laminate and 30 layers for thick laminate. Similarly for S-glass epoxy, 4 and 20 layers were used for thin and thick laminates respectively. The curing cycle followed in the making of the composite is mentioned in figure 1.

![Figure 1: Curing cycle](image)

Three point bend specimens as per ASTM D 2344 are prepared. Fixtures mentioned in ASTM 1425 are prepared and the interlaminar shear strength is estimated. Volume fraction of the fiber, matrix and void content of the fabricated samples is estimated by ASTM 3171 and its value is shown in table 1. Diamond cutting machine is used to generate thick and thin samples as per the dimensions mentioned in ASTM D 2344 and ASTM C 1425.
Table 1. Sample dimensions and volume fraction of Glass epoxy composite

| ASTM standard | Material used | Sample dimension in mm | Number of specimens | Number of layers | Thickness of the laminate in mm | Volume fraction in % | V_f | V_m | V_v |
|---------------|--------------|------------------------|---------------------|-----------------|--------------------------------|----------------------|-----|-----|-----|
| 2344          | E glass epoxy | 32 X 10 X 2            | 6                   | 6               | 2                              | 57.2                 | 42.7 | 0.1 |
| 2344          | E glass epoxy | 80 X 10 X 10           | 6                   | 30              | 10                             | 57.4                 | 42.4 | 0.2 |
| 1425          | S glass epoxy | 30 X 15 X 2            | 8                   | 4               | 2                              | 61                   | 38.1 | 0.9 |
| 1425          | S glass epoxy | 30 X 15 X 10           | 8                   | 10              | 10                             | 60.8                 | 38.7 | 0.5 |

Table 2. Sample dimensions of glass epoxy composite as per ASTM 2344 for thin laminate

| Length in mm | Thickness in mm | Width in mm | Density in g/cm³ |
|--------------|-----------------|-------------|------------------|
| T            | C               | B           | A                |
| T            | C               | B           | A                |
| T            | C               | B           | A                |
| T            | C               | B           | A                |
| 31.88        | 2.32            | 2.42        | 2.39             | 2.37            | 9.94          | 9.90          | 9.94          | 9.92          | 1.604            |
| 31.89        | 2.36            | 2.34        | 2.31             | 2.33            | 10            | 9.92          | 9.98          | 9.98          | 1.635            |
| 31.07        | 2.35            | 2.34        | 2.35             | 2.34            | 10            | 9.97          | 10            | 10            | 1.622            |
| 32.10        | 2.36            | 2.36        | 2.34             | 2.35            | 11.10         | 10            | 11            | 11.05         | 1.594            |
| 32.17        | 2.37            | 2.38        | 2.34             | 2.36            | 9.92          | 11.0          | 9.96          | 9.94          | 1.593            |
| 32.34        | 2.34            | 2.32        | 2.32             | 2.32            | 10.04         | 10.10         | 10.09         | 10.07         | 1.636            |

Tables 2 and 3 shows the sample dimensions of glass epoxy composite fabricated as per ASTM 2344 for thin and thick laminates respectively.

Table 3. Sample dimensions of glass epoxy composite as per ASTM 2344 for thick laminate

| Length in mm | Thickness in mm | Height in mm | Density in g/cm³ |
|--------------|-----------------|--------------|------------------|
| T            | C               | B            | A                |
| T            | C               | B            | A                |
| T            | C               | B            | A                |
| T            | C               | B            | A                |
| 80.05        | 9.81            | 10.18        | 10.12            | 10.03          | 10.16          | 10.15          | 10            | 10.10         | 1.686            |
| 80.09        | 10.10           | 10.06        | 10.07            | 10.07          | 10.12          | 10.05          | 9.95          | 10.19          | 1.662            |
| 80.14        | 10.10           | 10.22        | 10.14            | 10.15          | 9.97           | 9.89           | 9.81          | 9.89          | 1.696            |
| 80.15        | 10.15           | 10.16        | 10.21            | 10.17          | 9.84           | 9.93           | 9.98          | 9.91          | 1.708            |
| 80.20        | 10.21           | 10.09        | 9.91             | 10.07          | 10.04          | 10.05          | 9.98          | 10.02         | 1.701            |
| 80.40        | 10.11           | 10.07        | 10.06            | 10.08          | 9.78           | 9.84           | 9.91          | 9.94          | 1.694            |
| 80.17        | 10.08           | 10.13        | 10.09            | 10.10          | 9.99           | 9.99           | 9.94          | 10.02         | 1.69              |

The abbreviation T, C, B indicates the measured top, center, bottom specimen dimensions of the fabricated laminate. ‘A’ indicates the average value of the specimen dimensions.
2.2 Finite element analysis

The experimentally obtained results are thus compared with the published results and the finite element analysis is carried out in ANSYS. Shell 281 is used to model thin and thick laminates. The element has four corner nodes, four mid side nodes and each node has three translational and three rotational degrees of freedom.

There are three modules in ANSYS. In the preprocessor module, shell 281 from ANSYS library is selected and the sample dimension mentioned in table 1 is generated. From literature review, the mechanical properties of the constituents of test specimen used in ASTM 2344 and ASTM 1425 are taken. The estimated elastic constants are shown in table 4, where the volume fractions of the fibre and matrix are computed experimentally. In the preprocessor module, the geometric model is converted into finite element model by shell 281.

![Finite element model of thin laminate by ASTM D2344 (Left) and ASTM C1425 (Right).](image1)

Figure 3: Finite element model of thin laminate by ASTM D2344 (Left) and ASTM C1425 (Right).

For thin laminate, 5124 and 1600 are the corresponding number of nodes and elements for the sample dimension mentioned in ASTM D 2344. Similarly for thick laminate, 7481 and 2400 are the number of nodes and elements. To obtain convergence, discretization of the domain is made thus accounting to the variation in the number of nodes and elements in thin and thick laminate. Finite element model of the thin and thick laminate by ASTM C 1425 has 1433 nodes and 448 elements. This homogeneity in the number of nodes and elements is due to the analogous boundary conditions incorporated in experimental work and finite element analysis. Figure 3 shows finite element model. For thin and thick laminate, the number of nodes and elements are same since section offset is used to accommodate the variation in the thickness. The obtained finite element model is subjected to the boundary conditions mentioned in the standards and the load is applied from the experimentally obtained values. Finally, in the general post processor the comparison of obtained interlaminar shear strength is made. The details on the distribution of interlaminar shear strength are mentioned in table 5 for thin and thick laminates. It is inferred that the experimentally obtained interlaminar shear strength value is in very good correlation with the analysis carried out by finite element method for thin and thick laminates.

![ILSS at 717.12 N on Thin Laminate (Left) and ILSS at 2178.8 N on Thick Laminate (Right).](image2)

Figure 4: ILSS at 717.12 N on Thin Laminate (Left) and ILSS at 2178.8 N on Thick Laminate (Right).

Figure 4 shows symmetric distribution of ILSS in thin and thick laminate. Woven fabric is used in the present work and its equivalent elastic constants are provided as input in the pre-processor. It infers that there is uniform distribution of load between the fiber and matrix. The minimum and maximum values of ILSS in thin laminate are 2.17 MPa and 19.55 MPa. For thick laminate, the highest and least values of ILSS are 16.61 MPa and 2.5 MPa.
Figure 5 shows the distribution of interlaminar shear stress in thick and thin laminate, and its values are 16.17MPa and 36.94MPa respectively.

Table 4. Estimated elastic constants at 57.2 % of volume fraction of fiber

| Elastic constant | $V_f @ 0.572$ |
|------------------|---------------|
| $E_1$(GPa)       | 24.45         |
| $E_2$(GPa)       | 24.45         |
| $E_3$(GPa)       | 6.99          |
| $\theta_{12}$    | 0.1683        |
| $\theta_{23}$    | 0.024         |
| $\theta_{13}$    | 0.024         |
| $G_{12}$ (GPa)   | 1.99          |
| $G_{23}$ (GPa)   | 0.85          |
| $G_{13}$ (GPa)   | 0.85          |

Table 5. Distribution of interlaminar shear strength in thin and thick E - glass epoxy laminates

| Load in N | ILSS in MPa | Ansys | Load in N | ILSS in MPa | Ansys |
|-----------|-------------|-------|-----------|-------------|-------|
|            | Experimental method |       |           | Experimental method |       |
| 2178.8     | 16.13       | 16.61 | 717.12    | 22.88       | 19.55 |
| 2254.5     | 16.84       | 16.24 | 784.75    | 25.15       | 21.38 |
| 2261.0     | 16.81       | 16.28 | 789.60    | 25.24       | 21.40 |
| 2270.7     | 17.17       | 16.35 | 784.21    | 25.18       | 21.53 |
| 2271.6     | 16.90       | 16.36 | 831.8     | 24.02       | 22.46 |
| 2290.3     | 16.74       | 16.5  | 823.60    | 26.56       | 22.68 |
| 2254.48    | 16.76       | 16.39 | 788.51    | 24.83       | 21.5  |
The figure 6 shows the distribution of load vs. ILSS for thin and thick laminates. In case of thick laminate, when the applied load is 2178 N, its ILSS value by experimental method and ANSYS is noticed to be 16 MPa and 16.6 MPa respectively. When the load was varied to 2254.5 N there is a rise in the experimentally computed ILSS value. Also, an initial fall and subsequent rise is seen in the ANSYS data. Due to the variation in the density of specimen there is a gradual increase of ILSS in the experimental data, but in the case of finite element analysis the density remains constant throughout since extended rule of mixtures is incorporated. In case of thin laminate, when a load of 717.12 N is applied, an ILSS value of 22.88 MPa and 19.55 MPa for experimental method and finite element analysis is recorded respectively. There is a linear increase in ILSS values obtained from finite element analysis. Due to the non-uniform transfer of load in the specimen, the experimental work shows slight deviation from a linear path.

2.3. Experimental setup for ASTM C 1425

The main purpose of the fixture is to allow for uniform axial compression of the specimen, and to provide lateral support to prevent buckling. Test fixtures have been used successfully to evaluate the interlaminar shear strength of glass epoxy composite. The fixture consists of one hollow cylinder (sleeve), two pistons and two semi cylindrical spacers. The material used for manufacturing the fixture is mild steel. When using a slotted-body or two semi cylindrical spacers, the gap not larger than 1 % of the specimen thickness exists between the specimen and each spacer. To ensure uniform axial loading, the pistons should be concentric and form a tight clearance fit with the sleeve or hollow cylinder (that is, the pistons should be able to slide without friction within the sleeve). This can be achieved by meeting tight cylindricity requirements for the inner diameter of the sleeve and the outer diameter of the piston.
Table 6. Sample dimensions of S-glass epoxy composite as per ASTM C 1425 for thin laminate

| Length in mm | Width in mm | Thickness in mm |
|--------------|-------------|-----------------|
| 30.05        | 14.8        | 2.15            |
| 30.04        | 14.7        | 2.25            |
| 30.02        | 14.8        | 2.2             |
| 30.08        | 14.7        | 2.15            |
| 29.8         | 14.76       | 2.25            |
| 29.94        | 14.75       | 2.18            |
| 29.9         | 14.8        | 2.2             |
| 29.95        | 14.75       | 2.25            |

Table 7. Notch dimensions for thin laminate in mm

| Top right depth | Top left depth | Top right width | Top left width | Bottom right depth | Bottom left depth | Bottom right width | Bottom left width |
|-----------------|----------------|-----------------|----------------|--------------------|-------------------|--------------------|-------------------|
| 0.957           | 1.043          | 0.58            | 0.604          | 0.909              | 0.949             | 0.55               | 0.508             |
| 1.085           | 1.08           | 0.518           | 0.57           | 1.003              | 1.043             | 0.597              | 0.563             |
| 0.912           | 0.92           | 0.498           | 0.534          | 0.898              | 0.927             | 0.557              | 0.584             |
| 0.977           | 1.024          | 0.5             | 0.53           | 1.037              | 0.995             | 0.501              | 0.548             |
| 0.981           | 0.962          | 0.522           | 0.582          | 0.97               | 0.993             | 0.497              | 0.547             |
| 0.886           | 0.88           | 0.551           | 0.545          | 1.02               | 0.983             | 0.545              | 0.491             |
| 0.939           | 0.952          | 0.461           | 0.515          | 1.054              | 0.986             | 0.489              | 0.519             |
| 0.887           | 0.855          | 0.504           | 0.551          | 0.979              | 1.013             | 0.497              | 0.501             |

Tables 6 and 7 shows the sample dimensions fabricated as per ASTM C 1425. The details of the notch are shown in table 8 and 9 for thin and thick laminate respectively.

Table 8. Sample dimensions of glass epoxy composite as per ASTM C 1425 for thick laminate

| Length in mm | Width in mm | Thickness in mm |
|--------------|-------------|-----------------|
| 30.3         | 15.7        | 10              |
| 30.26        | 15.7        | 10              |
| 30.35        | 15.64       | 10              |
| 30.3         | 15.5        | 10              |
| 30.45        | 15.75       | 10              |
| 30.25        | 15.45       | 10              |
| 30.23        | 15.45       | 10              |
| 30.43        | 15.65       | 10              |

Table 9. Notch dimensions for thick laminate in mm

| Top right depth | Top left depth | Top right width | Top left width | Bottom right depth | Bottom left depth | Bottom right width | Bottom left width |
|-----------------|----------------|-----------------|----------------|--------------------|-------------------|--------------------|-------------------|
| 4.56            | 4.8            | 0.633           | 0.61           | 4.82               | 4.49              | 0.74               | 0.711             |
| 4.83            | 4.7            | 0.683           | 0.649          | 4.5                | 4.75              | 0.62               | 0.64              |
| 4.85            | 4.44           | 0.675           | 0.661          | 4.54               | 4.65              | 0.626              | 0.635             |
| 4.74            | 4.74           | 0.638           | 0.636          | 4.54               | 4.65              | 0.626              | 0.635             |
| 4.82            | 5.04           | 0.685           | 0.666          | 4.01               | 4.59              | 0.639              | 0.708             |
| 4.58            | 4.98           | 0.611           | 0.65           | 4.17               | 4.2               | 0.636              | 0.606             |
| 4.57            | 4.76           | 0.614           | 0.659          | 4.58               | 4.8               | 0.671              | 0.692             |
| 4.16            | 4.45           | 0.648           | 0.649          | 4.87               | 4.61              | 0.62               | 0.685             |
The estimate elastic constants by extended rule of mixtures are presented in Table 10. The distribution of interlaminar shear strength in thin and thick S-glass epoxy laminates is shown in Table 11. From the reference value [6] the interlaminar shear strength value is observed to be 36 MPa. In the present work the experimentally obtained mean value is 34.98 MPa while from ANSYS is 36.99 MPa. Therefore it is inferred that the deviation obtained is agreeable and the correctness of the assumptions made in estimating the elastic constants is verified. It implies uniform transfer of load between the fiber and the matrix while experimental work is conducted.

**Table 10.** Estimated elastic constants at 61 % of volume fraction of fiber

| Elastic constant | V_f @ 0.61 |
|------------------|------------|
| E_1 (GPa)        | 35.72      |
| E_2 (GPa)        | 35.72      |
| E_3 (GPa)        | 12.86      |
| \( \theta_{12} \) | 0.095      |
| \( \theta_{23} \) | 0.912      |
| \( \theta_{13} \) | 0.912      |
| G_{12} (GPa)     | 4.42       |
| G_{23} (GPa)     | 4.41       |
| G_{13} (GPa)     | 4.41       |

**Table 11.** Distribution of interlaminar shear strength in thin and thick S-glass epoxy laminates

|                     | Thick laminate , 10mm | Thin laminate , 2mm |
|---------------------|-----------------------|---------------------|
| Load in N           | ILSS in MPa           | Load in N           | ILSS in MPa |
|                     | Experimental method   | Ansys               | Experimental method | Ansys    |
| 1187                | 11.63                 | 11.92               | 1888.19             | 22.38    | 24.15   |
| 1610                | 16.53                 | 16.17               | 2453.29             | 30.9     | 31.38   |
| 2284                | 23.01                 | 22.95               | 2649.33             | 32.24    | 33.89   |
| 2682                | 28.36                 | 26.95               | 2879.36             | 35.29    | 36.83   |
| 2747                | 28.59                 | 27.6                | 2887.81             | 34.84    | 36.94   |
| 3840                | 38.39                 | 38.58               | 3024.32             | 35.85    | 38.68   |
| 3858                | 40.14                 | 38.76               | 3525.92             | 41.21    | 45.1    |
| 4088                | 42.53                 | 41.08               | 3830.04             | 47.17    | 48.99   |
| Average             | 2787                  | 28.64               | 28                   | 2892.28  | 34.98   | 36.99   |

Reference value [6] 36 MPa

**Figure 8:** Load vs. ILSS plots for Thick (Left) and Thin (Right) laminates.

Figure 8 shows the distribution of load Vs. ILSS for thick and thin laminates. In both the cases there is a uniform increase in ILSS for increase in load. This is due to uniform transfer of load between
the fibre, matrix and fibre-matrix interface. The average experimental and finite element analysis values of ILSS in thick laminate are 28.64 MPa and 28 MPa respectively. In reference [6], the ILSS for thin laminate is 36 MPa. In the present work, the ILSS for thin laminate is obtained to be 34.98 MPa and 36.99 MPa for experimental method and finite element analysis respectively. The deviation of experimental and finite element analysis values with the reference value is agreeable.

3. Results and Discussions

In this section, the results and discussions are interpreted. In the heading 4.1, the interlaminar shear strength for the specimen fabricated by the procedure ASTM D 2344 is shown for thin and thick laminate by experimental method. Similarly section 4.2 shows the distribution of the results by ASTM C 1425.

3.1 Three point bend specimen – ASTM D 2344

The mean interlaminar shear strength for thin laminate by experimental method and finite element analysis is observed to be 24.83 MPa and 21.5 MPa respectively. Similarly, the mean ILSS for thick laminate is 16.76 MPa from experimental method and by finite element method it is 16.39 MPa. The deviation from both the methods for thin and thick laminate is 13% and 2.2 % respectively. The density of the fabricated thin and thick laminate is observed to be 1.61 g/cc and 1.69 g/cc respectively. This variation in density of the fabricated laminate accounts for the improper transfer of load between the fiber, matrix and fiber matrix interface in thin laminate. Figure 8 shows the Strain vs. ILSS plot for thick and thin laminates.

3.2. Double notched specimen – ASTM C 1425

The average interlaminar shear strength in thin S-glass epoxy composite by experimental method and finite element analysis is 34.98 MPa and 36.99 MPa respectively. Likewise, the average ILSS value by experimental method and finite element analysis for thick laminate is 28.64 MPa and 28 MPa respectively. The deviation obtained from both the methods for thin and thick laminate are 5.7% and 2.2 % respectively. From this, it is inferred that the load transfer between the fiber and matrix is uniform. It is also observed that the volume fraction of fiber and matrix is, 61% and 38%.

Figure 9: Strain Vs. ILSS plot for thick (Left) and thin (Right) Laminate

Figure 10: Strain vs. ILSS plot for thick (Left) and thin (Right) laminates
4. Conclusions

1. From published literature [6], the interlaminar shear strength is 36 MPa. While estimating the same by adopting the procedure mentioned in ASTM C 1425, 34.98 MPa and 36.99 MPa is achieved for thin laminate by experimental method and finite element analysis by ANSYS. Its corresponding strain is 0.0435.

2. For ASTM 1425, the mean interlaminar shear stress by finite element analysis for thick laminate is 28 MPa and its strain is 0.0329.

3. In ASTM C 1425, fixtures consisting of hollow cylinder, top and bottom piston, semi cylindrical spacers are used to hold the specimen for thick and thin laminates. Compressive load is applied which enables uniform transfer of load from fibers to resin. Therefore it is recommended over ASTM D 2344 to estimate interlaminar shear strength.

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