Shear properties of pultruded fiber reinforced polymer composite materials

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Abstract. This paper focuses on the mechanical properties of PFRP composite materials. Especially, relationship between shear property and the other mechanical properties of PFRP composite materials is investigated through comparison between experimental and theoretical results. The shear property of PFRP composite specimen is calculated from the theoretical equations which were suggested in previous studies. In addition, comparison between the shear property determined by the tensile test and the shear property calculated from theoretical equations is conducted and discussed. It was found that the theoretically predicted shear modulus of elasticity considering contiguity is close to the shear modulus of elasticity obtained by the 45° off-axis tensile test.

1. Introduction

The pultruded fiber reinforced polymer plastic (PFRP) is one of the most actively studied composite materials for the structural member in construction industries [1]. Pultrusion is a continuous manufacturing process for mass production with good mechanical properties. The PFRP is considered as an orthotropic (transversely isotropic) material because fibers are placed to the longitudinal direction of the member [2].

The performance of an engineering material is often measured by the mechanical properties and static behavior such as tensile, compressive, shear or dynamic behavior in both normal and adverse test environments. This information of performance is important to take the proper material in a given application and designing a structure with the material [3].

The stiffness properties can be determined by experimental measurements, but an experimental set of measurements determines the properties of a fiber-matrix system produced by a single manufacturing process. When any change in the system variables occurs, additional measurements are required. These experiments may become time consuming and cost prohibitive [4]. Therefore, it is necessary to study the prediction of material properties of fiber reinforced composites.

This study focuses on the mechanical properties of PFRP composite materials. Especially, relationship between shear property and the other mechanical properties of PFRP composite materials is investigated through comparison between experimental and theoretically predicted results.
2. Theoretical calculation method tensile test of PFRP composite

To determine the mechanical properties of PFRP structural members, PFRP composite coupon specimens are used in the test. Width of PFRP composite coupon specimens is 600 mm and thickness of PFRP composite coupon specimens is 5 mm. Weight ratio of fiber is 60% and weight ratio of matrix is 40%. Typical Poisson's ratio of fiber and matrix is adopted from the reference [5]. Properties of PFRP composite coupon specimens are given in table 1.

Table 1. Properties of PFRP composite.

| Properties of PFRP composite coupon specimen | Width (mm) | Modulus of elasticity of fiber ($E_f$, GPa) | Modulus of elasticity of matrix ($E_m$, GPa) | Shear modulus of elasticity of fiber ($G_f$, GPa) | Shear modulus of elasticity of matrix ($G_m$, GPa) | Volume ratio of fiber ($V_f$, %) | Poisson’s ratio of fiber ($\nu_f$) | Volume ratio of matrix ($V_m$, %) | Poisson’s ratio of matrix ($\nu_m$) |
|-----------------------------------------------|------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|---------------------------------|-------------------------------|---------------------------------|-------------------------------|
| Width (mm)                                    | 600        | 72.50                           | 4.00                             | 30.21                            | 1.50                             | 41.19                            | 0.22                          | 58.81                            | 0.33                          |

To determine the tensile strength and modulus of elasticity in longitudinal direction and transverse direction, tensile tests in longitudinal direction and transverse direction are conducted. There are several test methods of shear test of composite materials such as ±45° off-axis tensile shear test, Iosipescu shear test, V-notched rail shear test, etc. The ±45° off-axis tensile shear test is one of the most popular testing methods for the pultruded composite structural profile. To determine the shear strength and shear modulus of elasticity, 45° off-axis tensile tests are conducted. The test information and stress-strain curve are detailed in table 2 and summary of test results is given in table 3.

Table 2. Test specimen dimension and stress-strain curve.

| Test                                                    | Specimen dimension (Length*width*thickness) | Stress-strain curve |
|---------------------------------------------------------|--------------------------------------------|---------------------|
| Tensile test in longitudinal direction (ASTM D 3039/D 3039 [6]) | 250mm*25mm*5mm                              |                     |
Tensile test in transverse direction (ASTM D 3039/D 3039 [6])

Tensile test in 45° off-axis direction (ASTM D 3518/D 3518 [7])

Table 3. Summary of average test results.

| Test                                | Maximum stress (MPa) | Modulus of elasticity (GPa) | Poisson’s ratio (ν₁₂) |
|-------------------------------------|----------------------|-----------------------------|-----------------------|
| Tensile test in longitudinal direction | 496.30               | 36.39                       | 0.33                  |
| Tensile test in transverse direction    | 23.86                | 9.89                        | -                     |
| Tensile test in 45° off-axis direction    | 24.50                | 5.13                        | -                     |

3. Theoretical prediction of the shear modulus of elasticity

In theoretical analysis, the shear property of PFRP composite specimen is calculated from the theoretical equation which was suggested in previous studies.

According to the rule of mixtures [8], the shear property of PFRP composite materials is determined in the mechanics of materials approach by presuming that the shearing stresses on the fiber and on the matrix are the same. The shear modulus of elasticity is determined by equation (1).

\[
G_{12} = \frac{G_f G_m}{V_f G_f + V_m G_m}
\]

where, \(G_{12}\) is the shear modulus of elasticity, \(G_f\) is the shear modulus of elasticity of fiber, \(G_m\) is the shear modulus of elasticity of matrix, \(V_f\) is the volume ratio of fiber, and \(V_m\) is the volume ratio of matrix.

According to Jones’s study [8], the shear modulus of orthotropic composite materials was suggested as equation (1). The shear modulus of the PFRP composite used in tensile test is calculated from equation (1) and calculated result is given in table 4.
Table 4. Theoretically predicted result by equation (1).

| $G_f$ (GPa) | $G_m$ (GPa) | $V_f$ (%) | $V_m$ (%) | $G_{12}$ (GPa) |
|-------------|-------------|-----------|-----------|----------------|
| 30.21       | 1.50        | 41.19     | 58.81     | 4.42           |

In addition, Jones’s study suggested as equations which considered the effect of actual fiber arrangement. In the fabrication of fiberous composite materials, the fibers are often somewhat randomly placed rather than being packed in a regular array. Therefore, the theoretical analysis for the modulus of composite materials with regular arrays must be modified to account for the fact that fibers are contiguous, i.e., that fibers touch each other rather than being entirely surrounded by matrix material. If $C$ denotes degree of contiguity, then $C=0$ corresponds to no contiguity (isolated fibers) and $C=1$ corresponds to perfect contiguity (all fibers are in contact) as shown in figure 1 [8].

![Figure 1. Extremes of fiber contiguity](image)

For the elasticity approach in which the contiguity is considered, the modulus of elasticity in the transverse direction was suggested as equation (2).

$$
E_{22} = 2\left[1 - v_f + (v_f - v_m)V_m\right] \times \frac{K_f(2K_m + G_m) - G_m(K_f - K_m)V_m}{(2K_m + G_m) + 2(K_f - K_m)V_m} + \frac{K_f(2K_m + G_f) + G_f(K_m - K_f)V_m}{(2K_m + G_f) - 2(K_m - K_f)V_m}
$$

where, $E_{22}$ is the modulus of elasticity in the transverse direction, $G_f$ is the shear modulus of elasticity of fiber, $G_m$ is the shear modulus of elasticity of matrix, $V_f$ is the volume ratio of fiber, $V_m$ is the volume ratio of matrix, $v_f$ is the Poisson’s ratio of fiber, $v_m$ is the Poisson’s ratio of matrix, $K_f$ is the transverse plane strain bulk modulus of fiber, $K_m$ is the transverse plane strain bulk modulus of matrix, and $C$ is the degree of contiguity.

In equation (2), the parameters $K_f$ and $K_m$ are calculated by equation (3) and equation (4).

$$
K_f = \frac{E_f}{2(1-v_f)}
$$

$$
K_m = \frac{E_m}{2(1-v_m)}
$$

From a practical point of view, $C$ would be determined by comparison of theoretical curves of $E_{22}$ versus ($V_f$ or $V_m$) for various values of $C$ with experimental results. Therefore, $C$ of the test specimen was determined by comparison with the tensile test result in transverse direction and equation (2). The
result of comparing with the tensile test in transverse direction result and equation (2) is given in table 5. Mechanical properties of PFRP composite specimen obtained by the tensile tests are applied to the parameters in equation (2).

Table 5. Contiguity from equation (2).

| $E_{22}$ (GPa) | $G_f$ (GPa) | $G_m$ (GPa) | $V_f$ (%) | $V_m$ (%) | $\nu_f$ | $\nu_m$ | $C$ |
|---------------|-------------|-------------|-----------|-----------|---------|---------|-----|
| 9.89          | 30.21       | 1.50        | 41.19     | 58.81     | 0.22    | 0.33    | 0.32 |

In addition, equation (5) was suggested in Jones’s study for calculating the shear modulus of elasticity.

\[ G_{12} = (1 - C)G_m \frac{2G_f - (G_f - G_m)V_m}{2G_m + (G_f - G_m)V_m} + CG_f \frac{(G_f + G_m) - (G_f - G_m)V_m}{(G_f + G_m) + (G_f - G_m)V_m} \]  
(5)

where, $G_{12}$ is the predicted shear modulus of elasticity, $G_f$ is the shear modulus of elasticity of fiber, $G_m$ is the shear modulus of elasticity of matrix, $V_f$ is the volume ratio of fiber, $V_m$ is the volume ratio of matrix, $\nu_f$ is the Poisson’s ratio of fiber, $\nu_m$ is the Poisson’s ratio of matrix, and $C$ is the degree of contiguity.

The shear modulus of the PFRP composite used in tensile test is calculated from equation (5). The result of calculation is given in table 6. Properties of PFRP composite used in tensile tests are applied to the parameters in equation (5).

Table 6. Predicted shear modulus of elasticity by equation (5).

| $G_f$ (GPa) | $G_m$ (GPa) | $V_f$ (%) | $V_m$ (%) | $\nu_f$ | $\nu_m$ | $C$ | $G_{12}$ (GPa) |
|-------------|-------------|-----------|-----------|---------|---------|-----|----------------|
| 30.21       | 1.50        | 41.19     | 58.81     | 0.22    | 0.33    | 0.32 | 5.15           |

4. Comparison

Experimental results and theoretical are compared to determine the reliability of the theoretical analysis. Comparison of experimental and theoretical results is given in table 7.

Table 7. Comparison of the shear modulus of elasticity.

| Description                                      | $G_{12}$ (GPa) | Difference (%) | Remark    |
|--------------------------------------------------|----------------|----------------|-----------|
| Tensile test in 45° off-axis direction           | 5.13           | -              | Tested    |
| Calculated result by equation (1)                | 4.42           | -13.84         | Predicted |
| Calculated result by equation (5)                | 5.15           | 0.39           | Predicted |

As a result of comparison with the theoretical and experimental results of the shear modulus of elasticity, the difference obtained by equation (1) is $-13.84\%$, the difference obtained by equation (5) is $0.39\%$. In the case of equation (5), the predicted shear modulus of elasticity showed a reliable difference compared with experimental results.

In the results of comparison between calculation result of equation (1) and equation (5), the result of equation (5) showed $13.45\%$ less difference than the result of equation (1). Therefore, in the
theoretical analysis for the shear modulus of PFRP composite materials, if the arrangement of fibers is considered it may reduce the difference between experimental and theoretical results. Also, it is thought that the prediction of shear modulus of PFRP composite materials is possible using equation (5).

5. Conclusion
In this study, the mechanical properties of PFRP composite materials are investigated. Especially, relationship between the shear property and the other mechanical properties of PFRP composite materials is investigated through comparison between experimental and theoretical results. Results obtained in this study is as follows:

To determine the tensile strength and the modulus of elasticity in longitudinal direction and transverse direction, the tensile test in longitudinal direction and transverse direction is conducted. To determine the shear strength and the shear modulus of elasticity, the tensile test in 45° off-axis direction is conducted. As a result of the tensile tests, the modulus of elasticity in longitudinal direction is 36.39 GPa, the Poisson’s ratio is 0.33, the modulus of elasticity in transverse direction is 9.89 GPa, and the shear modulus of elasticity is 5.13 GPa. Standard deviation and coefficient of variation on the test results are evaluated and it was found that they are reliable.

In the theoretical analysis, the shear property of PFRP composite specimen is calculated from the theoretical equations which were suggested in previous studies. As a result of comparison between the theoretical and experimental results of the shear modulus of elasticity, the difference obtained by equation (1) is −13.84% and the difference obtained by equation (5) is 0.39%. In the case of equation (5), the theoretical shear modulus of elasticity showed a reliable difference when compared with experimental results. However, from the result by equation (1), the theoretical shear modulus of elasticity showed significant difference compared with experimental results.

In the results of comparison between predicted result by equation (1) and equation (5), the result of equation (5) showed 13.45% less difference than the result of equation (1). Therefore, in the theoretical analysis for the shear modulus of PFRP composite materials, considering the arrangement of fibers is considered to reduce the difference between the experimental and the theoretical results. In addition, the shear modulus of PFRP composite materials can be predicted from material properties of fiber and matrix of PFRP composites.

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