Tensile and compressive modulus of elasticity of pultruded fiber-reinforced polymer composite materials

J H Lee¹, S H Kim², J K Park³, W C Choi² and S J Yoon¹

¹Department of Civil Engineering, Hongik University, 94 Wausan-ro, Mapo-gu, Seoul 04066, Korea
²Department of Architectural Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Gyeonggi-do 13120, Korea
³Daehan EnC, #1401 Techdong SK®Techno Park, 124 Sagimakgol-ro, Jungwon-gu, Seongnam-si, Gyeonggi-do 13207, Korea

E-mail: sjyoon@hongik.ac.kr

Abstract. Many researches focused on the mechanical properties of steel and concrete have been carried out for applications in the construction industry. However, in order to clarify the mechanical properties of pultruded fiber-reinforced polymer (PFRP) structural members for construction, testing is needed. Deriving the mechanical properties of PFRP structural members through testing is difficult, however, because some members cannot be tested easily due to their cross-section dimensions. This paper reports a part of studies that attempt to present conservative results in the case of members that cannot be tested reasonably. The authors obtained and compared experimental and theoretical modulus of elasticity values. If the mechanical properties of PFRP members can be predicted using reasonable and conservative values, then the structure can be designed economically and safely even in the early design stages. To this end, this paper proposes a strain energy approach as a conservative and convenient way to predict the mechanical properties of PFRP structural members. The strain energy data obtained can be used to predict the mechanical properties of PFRP members in the construction field.

1. Introduction
In order to use composite material because of its outstanding material properties as a structural material in the construction field, it is important to understand its mechanical properties. Composite material produced by pultrusion, referred to as ‘pultruded fiber-reinforced polymer’ (PFRP) composite, has different properties in the longitudinal and transverse directions of the fiber. To analyze and design such composite structures, mechanical properties tests, such as tension, compression, shear, and bending tests, should be conducted. However, some profile sections of structural members produced by pultrusion may not allow testing according to ASTM and ISO test methods, especially for the transverse direction, because the test methods suggested by ASTM and ISO limit the length of the specimens required for tensile tests. Thus, many PFRP composite members cannot be tested using standard test methods.

Research into the mechanical properties of steel has been carried out for practical applications in the construction industry. According to McCormac, the stress-strain curve of steel is assumed to be the same for members in tension and compression. However, this assumption does not hold for PFRP
composite material. Recently, Kim et al measured and compared the tensile and compressive mechanical properties of PFRP composite members [1]. In this study, we compared the theoretical and experimental results of mechanical property tests of PFRP composite material for the conservative application of PFRP members in the construction field [1-4].

2. Theoretical predictions
The theoretical prediction method that is used to predict the mechanical properties of PFRP composite members applied in current construction is as follows. For the modulus of elasticity in the longitudinal direction \(E_{11}\), the ‘rule of mixtures’ is used to calculate the theoretical values of the PFRP composite properties. To calculate these values using the rule of mixtures, the volume ratio \((v_f, v_m)\) and modulus of elasticity \((E_f, E_m)\) of each component (fiber and matrix) are needed. Equation (1) is based on the rule of mixtures and is given by [5].

\[
E_{11} = E_f v_f + E_m v_m \tag{1}
\]

For the modulus of elasticity in the transverse direction \(E_{22}\), equation (2), proposed by Hopkins and Chamis, is used [5].

\[
E_{22} = E_m \left(1 - \sqrt{v_f} + \sqrt{v_f} \left(1 - \sqrt{v_f} \left(1 - E_m/E_f \right) \right)^{-1} \right)^{-1} \tag{2}
\]

Equations (1) and (2) enable the prediction of the modulus of elasticity values of PFRP composite members. Table 1 presents the calculated results.

Table 1. Calculation results for prediction of mechanical properties of PFRP composite members (fiber volume ratio 41.19%).

| Direction               | \(E_f\) (GPa) | \(v_f\) (%) | \(E_m\) (GPa) | \(v_m\) (%) | Modulus of elasticity (GPa) |
|-------------------------|--------------|-------------|---------------|-------------|----------------------------|
| Longitudinal direction \((E_{11})\) | 72.5        | 41.19       | 4             | 58.81       | 32.215                     |
| Transverse direction \((E_{22})\) |              |             |               |             | 7.955                      |
| Direction              | \(\sigma_f\) (MPa) | \(v_f\) (%) | \(\sigma_m\) (MPa) | \(v_m\) (%) | Ultimate strength (MPa)    |
| Longitudinal direction \((\sigma_{11})\) | 3400        | 41.19       | 65            | 58.81       | \(1.439 \times 10^3\)     |
| Transverse direction \((\sigma_{22})\) |              |             |               |             | 109.065                    |

3. Mechanical properties of composite material
To carry out the tests under both tension and compression, test specimens with 5-mm thickness were fabricated. The specimen is made of E-glass fiber for the reinforcing material and unsaturated polyester for the matrix. The fiber’s (including roving and fabric) volume ratio was 41.19 percent (weight ratio was 60%).

For the tests, 20 specimens (5 specimens for each test) were prepared. The tensile tests were carried out according to ASTM D 3039M-00 [6] and the compressive tests were carried out according to Yoon [7,8]. Table 2 presents the averaged test results and table 3 presents the specimen dimensions and stress-strain curves. The mechanical behavior of the pultruded composite material in the longitudinal direction is linear elastic and is mainly dependent on the characteristics of the fiber. However, the mechanical behavior of the pultruded composite in the transverse direction is nonlinear elastic and is largely dependent on the characteristics of polyester resin. The results obtained from
these tests were compared with the theoretically predicted results obtained following the method described in Section 2.

**Table 2. Tensile and compressive test results.**

| Test                                | Ultimate strength (MPa) | Modulus of elasticity (GPa) | Poisson’s ratio ($\nu_{12}$) |
|-------------------------------------|-------------------------|-----------------------------|-----------------------------|
| Tensile test in longitudinal direction | 496.30                  | 36.39                       | 0.33                        |
| Tensile test in transverse direction | 23.86                   | 9.89                        | -                           |
| Compressive test in longitudinal direction | 446.89                  | 38.76                       | 0.36                        |
| Compressive test in transverse direction | 138.70                  | 13.30                       | 0.13                        |

**Table 3. Specimen dimensions and stress-strain curves.**

| Test                                | Specimen dimensions (length*width*thickness) | Stress-strain curve |
|-------------------------------------|----------------------------------------------|---------------------|
| Tensile test in longitudinal direction | 250 mm*25 mm*5 mm                           | ![Tensile strain curve](image) |
| Tensile test in transverse direction  | 250 mm*25 mm*5 mm                           | ![Tensile strain curve](image) |
4. Comparison
It is necessary to confirm whether the tensile properties of the composite material can be substituted by the compressive properties. Table 4 provides the ratios of the mechanical properties obtained from the tests of the PFRP composite specimens. According to the ratios, the modulus of elasticity and the ultimate strength can be substituted for each other when they are in the fiber direction. However, because the difference is large in the transverse direction of the fiber, they cannot be substituted for each other when they are in the transverse direction.

| Direction     | Modulus of elasticity (GPa) | Ultimate strength (MPa) | Ratio $(\text{1)/}\text{(2)}$ |
|---------------|-----------------------------|-------------------------|--------------------------------|
| Fiber         | $E_{11t}$                   | $\sigma_{11t}$          | 36.39                          |
|               | $E_{22t}$                   | $\sigma_{22t}$          | 9.89                           |
| Transverse    | $E_{11c}$                   | $\sigma_{11c}$          | 38.76                          |
|               | $E_{22c}$                   | $\sigma_{22c}$          | 13.30                          |

The test results were compared with the theoretically predicted results. The mechanical properties of the test specimens were predicted using the rule of mixtures described in above and table 1. Figures
1(a) and 1(b) present a comparison of the results for the modulus of elasticity and ultimate strength, respectively. The theoretically calculated values are represented by the checkered bar in each graph.

Figure 1 shows that the modulus of elasticity obtained by tensile testing may lead to a conservative design and, thus, the theoretically predicted value may also result in a more conservative design. However, prediction of the ultimate strength is not possible; the test results under tension and/or compression are significantly different from each other. Hence, to predict the ultimate strength of the material under tension and compression, further study is needed.

![Figure 1. Comparison of tensile test results: (a) modulus of elasticity and (b) ultimate strength.](image)

5. Suggested prediction method

According to Sakaguchi et al [9], the rule of mixtures is generally used only as an estimate of the modulus of elasticity rather than as a numerically accurate predictor. The rule of mixtures provides accurate predictions when the difference between the modulus of elasticity values of the two phases is small. To solve the problem for applying the rule of mixtures, the Hashin-Shtrikman model, Voigt-Reuss/Angew model, phenomenological model, etc have been used to predict the mechanical properties in dental composites. However, for the construction field, no reasonable prediction model is available to determine the mechanical properties of PFRP composite material. If a prediction model could estimate the mechanical properties of PFRP composite material used in construction, it would also be helpful for predicting the mechanical properties of structural members. The theoretical calculation method described earlier cannot accurately predict the mechanical properties of specimens under tension and compression.

In this paper, strain energy constants are suggested to predict the mechanical properties of PFRP composite material. If the strain energy constants for the PFRP composite material are known, then the mechanical properties can be predicted with reasonable accuracy. The recommended strain energy constants that can be used to predict the mechanical properties of PFRP are given in equations (3), (4), and (5) [5,9].

\[
\alpha v_f + b v_m = 1 \tag{3}
\]
\[
E_{11} = \left( a_1^2 v_f E_f^{-1} + b_1^2 v_m E_m^{-1} \right)^{-1} \tag{4}
\]
\[
E_{22} = a_2^2 E_f v_f + b_2^2 E_m v_m \tag{5}
\]

where the strain energy constants, \(a, b, a_1, a_2, b_1,\) and \(b_2\) can be expressed as \(a_{1t}, a_{2t}, b_{1t}, b_{2t}, a_{1c}, a_{2c}, b_{1c},\) and \(b_{2c}\) in tension and compression.

For example, if \(E_{11}\) and \(E_{22}\) obtained from tests and \(E_f\) and \(E_m\) obtained from general material properties listed in any composite textbook are known, then the strain energy constants, \(a_{1t}\) and \(b_{1t}\), may appear when equations (3) and (4) together are calculated, as given in table 5. These constants are suggested to predict the mechanical properties of PFRP (fiber volume ratio 41.19%). This method may
be able to predict the mechanical properties of PFRP members for construction. Therefore, if data about the mechanical properties of composite materials used in the construction industry can be obtained, then a model that can predict the mechanical properties of PFRP composite for structural members can be derived.

**Table 5.** Strain energy constants for test specimens (fiber volume ratio 41.19%) (i= √−1).

| Direction             | Constants | Compression |
|-----------------------|-----------|-------------|
|                       | Tension   |             |
| Longitudinal direction| $a_{lt}$  | 2.25-0.21i  |
|                       | $b_{lt}$  | 0.12+0.15i  |
| Transverse direction  | $a_{2t}$  | 0.42        |
|                       | $b_{2t}$  | 1.41        |

6. Conclusion

This study examined the tension and compression characteristics of PFRP composite material. The conclusions drawn from the study are as follows:

Modulus of elasticity values in the fiber direction ($E_{11}$), as obtained from tension and compression tests, can be used interchangeably in structural design. However, the modulus of elasticity values obtained from tension and compression tests in the transverse direction of the fiber ($E_{22}$) cannot be used interchangeably.

The theoretically predicted modulus of elasticity of a PFRP member may result in the conservative design of the member.

Ultimate strength predictions may not be feasible and require further study.

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