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Research Article

TENSILE AND COMPRESSIVE BEHAVIORS OF THE PULTRUDED GFRP LAMINA

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ABSTRACT

The use of composite materials in civil engineering is increasing day by day due to their superior priorities such as high strength to weight ratio, high corrosion resistance, and durability. One of the recent materials used in the civil engineering application is pultruded glass fiber reinforced polymer (GFRP). Many studies are available in the literature related to the behavior of component (structural) level of the pultruded GFRP; however, very limited data is available related to the behavior of the lamina level of the pultruded GFRP. Since the behaviors of the pultruded GFRP in longitudinal and transverse directions are quite distinct, it is aimed to provide the tensile and compressive behavior of the pultruded GFRP in terms of stiffness, capacity and failure modes. Pursuant to this goal, longitudinal and transverse direction of the pultruded GFRP laminas were tested under both compressive and tensile forces according to ASTM standards. A total of 12 specimens, three replicates for each type, were tested. Moreover, these tests were modelled with the aid of Abaqus. The numerical and experimental results revealed that the transverse strength of pultruded GFRP is much weaker than its longitudinal strength for both compressive and tensile forces. While the damages in tensile tests started in micro dimension and continued as macro and the result of the damage was progressive damage, the rapid progression of damages in compression experiments led to the development of catastrophic damage.

Keywords: Composite Material, Pultruded GFRP, Tensile, Compressive, Damage Analysis

1. INTRODUCTION

Many studies are available in the literature related to use of composite material in civil engineering applications (Ozbakkaloglu, 2013; Kara *et al.* 2015; Kara *et al.* 2016; Gemi *et al.* 2018; Gemi *et al.* 2019; Madenci 2019; Özütok and Madenci, 2017; Madenci and Özütok, 2017; Özütok *et al.* 2014; Özütok and Madenci, 2013). One of the newest composite materials used in civil engineering applications is pultruded glass fiber reinforced polymer (GFRP) (Gemi and Köroğlu, 2018). GFRP composites produced by pultrusion method are used both as a main material and as complementary material in the field engineering area. This type of composite materials have a long-lasting strength compared to other materials, high performance against environmental factors, lightweight, resistance to corrosion effects, electricity insulation, low density, effective mechanical resistance use has increased gradually (Gemi *et al.* 2020; Gemi, 2018). Due to high demand to these advanced materials, the understanding of mechanical behavior of pultruded GFRP composite structures is important for design. The studies of the pultruded GFRP to use as a structural member such as column, beam and etc. are gained attention (Yu *et al.* 2016; Lokuge *et al.* 2019; Muttashar *et al.* 2016; Kara *et al.* 2019).

In addition to studies related to structural (component) level of the pultruded GFRP, a limited research on pultruded GFRP as lamina level has been found in the literature (Al-saadi *et al.* 2019; Haj-Ali and Kilic, 2002; Bai *et al.* 2008; Feo *et al.* 2012; Xin *et al.* 2017). Zhang *et al.* (2018) performed tensile tests to examine the effects of the fiber orientation on material properties of the pultruded GFRP. Eight different fiber orientations were studied and it is concluded that fiber orientation has significant effect on the mechanical properties of the pultruded GFRP. Al-saadi *et al.* (2019) conducted a series of experiments to determine mechanical properties of the pultruded GFRP with different fiber orientations of $[0^\circ, \pm 50^\circ]$, $[0^\circ, \pm 45^\circ]$, $[0^\circ, \pm 56^\circ]$ and $[0^\circ, \pm 71^\circ]$. The result of the study revealed that strength and modulus of elasticity depend on the fiber orientation.

Production of multi-directional pultruded GFRP is rather stringent; therefore, uni-directional pultruded GFRP is generally manufactured due to the easy of production. In this study, single-layer pultruded GFRP composite laminas with fiber orientation of $[0^\circ]$ and $[90^\circ]$ were selected for experimental mechanic tests. Material properties are obtained by tensile and compressive tests according to ASTM standards. Modulus of elasticity, capacity and failure modes of pultruded GFRP composite laminas are analyzed and investigated. The specimens were cut out of the composite plates in the characteristic directions dictated by the fiber: (1) test in the direction of the fiber and (2) test in the direction transversal in the fiber.

2. EXPERIMENTAL STUDY

Tensile and compressive tests were conducted in order to obtain the mechanical properties of the pultruded GFRP composite, such as strengths and modulus of elasticity. The specimens were cut and tested according to ASTM standard test methods. The specimens are cut

out of the composite plates in the characteristic directions dictated by the fiber: (1) test in the direction of one of the yarn systems of the fiber (warp/weft for woven fabrics; braiding/inlay yarns for braids); and (2) test in the direction transversal or bias to the direction of the yarn systems in the fiber (bias for woven fabrics, perpendicular to the production direction for braids). A total of twelve specimens which can be categorized into four groups are taken from the pultruded GFRP profile. Three specimens used in tensile test and three specimens are used in compressive test for each group (longitudinal direction: 0° and transverse directions: 90°)

2.1. Tensile Test

The tensile test was performed according to ASTM D638 (Standard Test Method for Tensile Properties of Plastics). The test was conducted using a Shimadzu universal testing machine with a capacity of 100 kN. The test setup is depicted in Fig. 1. Tensile tests were conducted on the specimens with nominal dimensions of $250 \times 25 \times 6$ mm (length-width-thickness) and $150 \times 25 \times 6$ mm, in order to determine the tensile strength and the displacement in the longitudinal and transverse directions, respectively. The distances between the claws were 190 mm and 90 mm for longitudinal and transverse directions, respectively.



Fig. 1. Tensile test setup

2.2. Compressive Test

The compressive test is also conducted using Shimadzu universal testing machine and the test was performed according to ASTM D695 (Standard test method for compressive properties of rigid plastics). The test setup is illustrated in Fig. 2.



Fig. 2. Compressive test setup

In this case test speed is 1.5 mm/min. Compressive tests were conducted on the specimens with nominal dimensions of 150×25×6 mm (length-width-thickness) in both the longitudinal direction and the transverse direction, in order to determine the compressive strength and the displacements for both directions.

3. NUMERICAL STUDY

Numerical study was conducted in order to verify experimental results. The commercial software Abaqus was used to model compressive and tensile tests. Shell elements were utilized to mesh the pultruded GFRP. For this purpose S4R general purpose linear 4-sided shell element with reduced integration was used. Elastic properties of the pultruded GFRP was defined using elastic type of “Lamina”. Boundary conditions were defined to the region between the claws to simulate experimental study. The numerical model and boundary conditions are illustrated in Fig. 3.

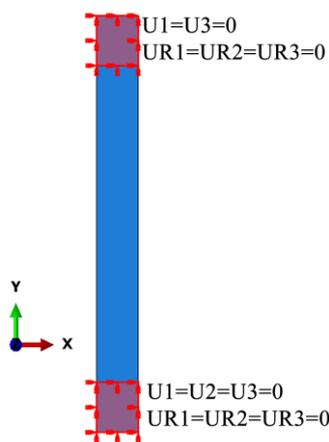


Fig. 3. The numerical model and boundary conditions

4. RESULTS

4.1. Tensile Test Results

Fig. 4 and Fig. 5 demonstrate the tensile test results of the longitudinal and transverse direction respectively

as well as the numerical results. According to the test results, average modulus of elasticity is approximately 23 GPa and 7 GPa for longitudinal and transverse directions, respectively (Madenci *et. al.* 2020). The test results showed that the tensile strength of longitudinal direction was 7.25 times higher than that of transverse direction. The average tensile strengths of the specimens for the longitudinal and transverse direction are 290 MPa and 40 MPa, respectively. The numerical results are also substantiate to the experimental results.

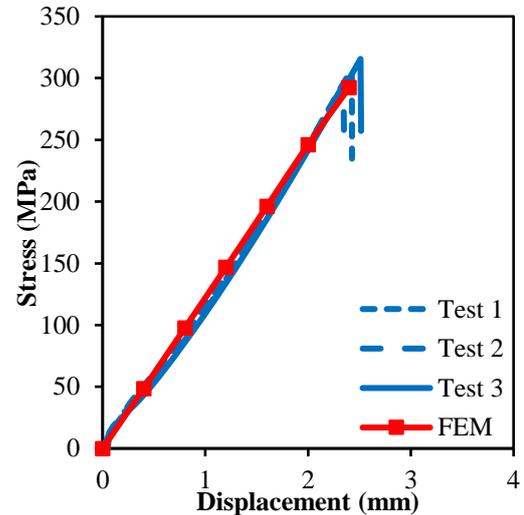


Fig. 4. The tensile test results of longitudinal direction

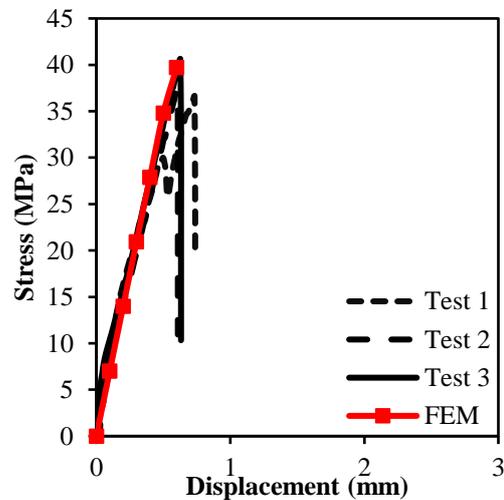


Fig. 5. The tensile test results of transverse direction

When the test results of the specimens (Fig. 4) and the photographs of the damage (Fig. 6) are investigated together, final failure was observed at stress value of 313 MPa and displacement value of 2.5 mm. Matrix crack sounds started to emerge at approximately 280 MPa stress and 2.26 mm displacement as initial damage. Addition to matrix cracks, it was observed that transfer cracks with debonding damage were occurred at the stress and displacement value close to final failure in (0°) fiber layers. As the loading continues, intra-interlaminar cracks occurred in the longitudinal direction and then fiber breakage together with veil damage has started to occur. As a result of fiber breaks in the other layers, final failure has occurred.

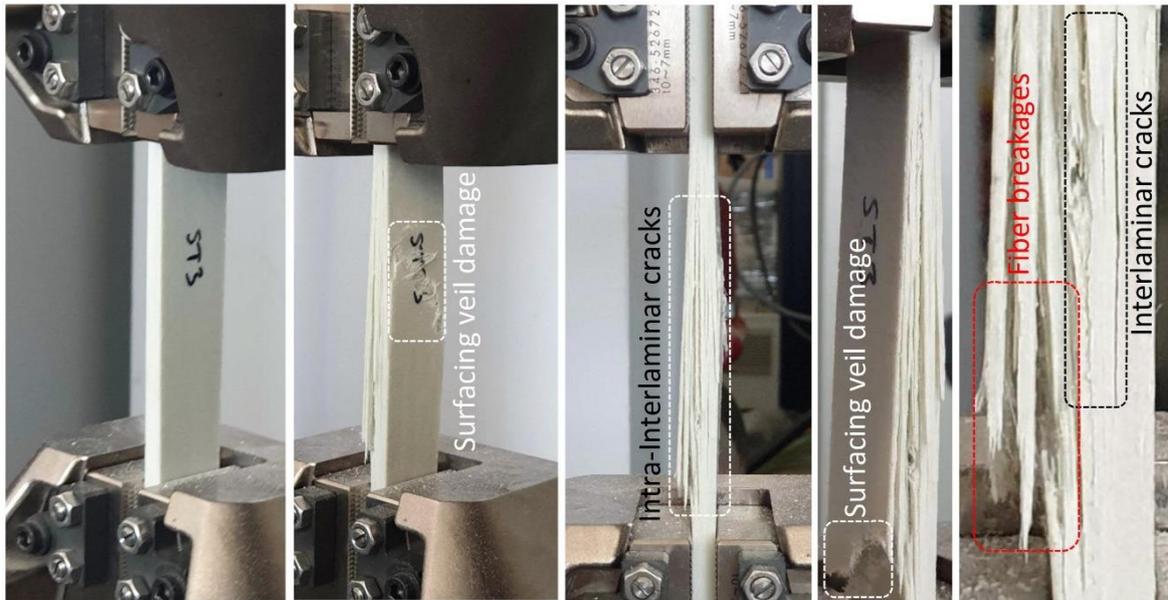


Fig. 6. Tensile test failure in the longitudinal direction

When the test results (Fig. 5) and the photographs of the damage (Fig. 7) of the specimens which were exposed to transverse tensile forces, maximum of 40.6 MPa stress and 0.62 mm displacement were observed among three specimens. Fluctuations at stress value of 35 MPa and displacement value of 0.5 mm were observed in the graph due to debonding damage occurring between the fibers perpendicular to the loading direction. Different from other specimens, debonding damage was observed at 29.7 MPa and 0.46 mm in Test 1. Matrix crack sounds were observed at same stress value in other specimens and it has continued to increase up to the resulting damage. While before debonding damage the load was carried together by (90°) fibers and veil surface, after debonding damage the load was carried by only veil surface. Damage to the transverse (90°) layer has progressed due to the damage occurred at randomly generated veil layers. Dense matrix damages were observed at cross section of the specimen as a result of separation of fiber matrix interfaces. The final failure for all three specimens was formed as splitting damage after surfacing veil damage.

4.2. Compressive Test Results

Fig. 8 and Fig. 9 demonstrate the compressive test results of the longitudinal and transverse direction, respectively. Test results revealed that compressive strength of longitudinal direction was much higher than that of transverse direction. Compressive strengths of the specimens for the longitudinal and transverse direction are 280 MPa and 85 MPa, respectively. Moreover, excellent correlation was obtained between numerical and experimental results.

The test results (Fig. 8) and the photographs of the damage (Fig. 10) of the specimens exposed to longitudinal compressive forces are investigated in detail. Maximum displacement (0.52 mm) and maximum stress (281 MPa) were obtained from Test 1. In compression tests, unlike tensile tests, after a certain stress value (about 250 MPa), deformation due to buckling was observed in the specimen. With the buckling damage, matrix crack sounds started to appear in the specimen.



Fig. 7. Tensile test failure in the transverse direction

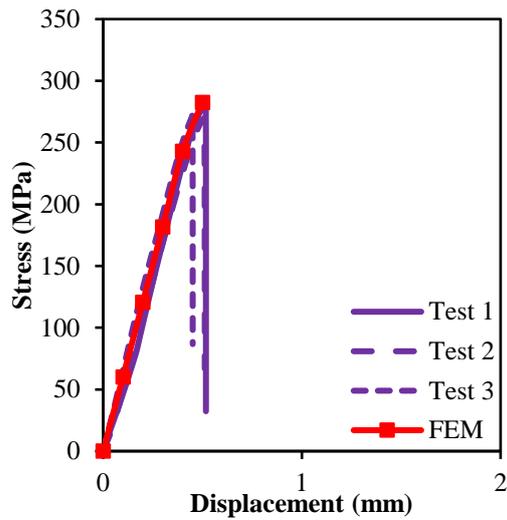


Fig. 8. The compressive test results of longitudinal direction

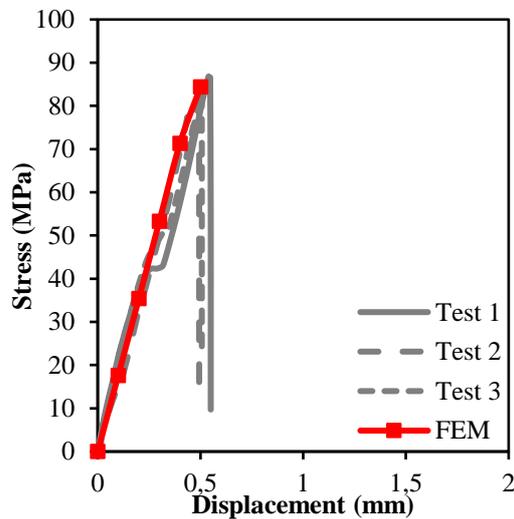


Fig. 9. The compressive test results of transverse direction

Local delamination damage has started to occur in the fiber direction between the layers and veil surfaces with the increase of intra-interlaminar cracks. At the maximum stress level, delamination damages on the specimen progressed rapidly and the final failure occurred. When the damage photographs are examined, the delamination between the layers and the interlayers formed by the effect of micro buckling on all layers is clearly observed. In the delamination zone, longitudinal direction (0°) fibers showed debonding damage, while fiber breakages were observed in the veil surfaces.

The test results (Fig. 9) and the photographs of the damage (Fig. 11) of the specimens which were exposed to transverse compressive forces are given. When Fig. 9 is examined, it is interpreted that debonding damage and matrix cracks occurred due to compression effect in transverse direction fiber layers at 39-53 MPa for Test 1 and 2, and at 76 MPa for Test 2. Despite the formation of debonding and matrix cracks, the veil surfaces surrounding the fiber layers (90°) continued to carry load. When the test graph of Test 1 is examined, it is seen that it represented better damage development during compression and the formation of matrix cracks in the stress value of 83 MPa at veil surfaces caused fluctuations in stress value. With the increase of the applied load, the debonding and matrix crack damages on the specimens were combined and the final failure was formed as splitting at an angle of 45° at 0.55 mm displacement and 86.6 MPa stress value. When the damage photographs given in Fig. 11 are examined closely, it is observed that there is intensive debonding and matrix cracks damages in transverse direction (90°) fibers and fiber breakage damages occur in the veil surfaces due to micro buckling. In all three specimens, the final failure can be interpreted as the damage caused by the transverse direction (90°) fibers which leads to splitting damage in the form of shear planes at an angle.

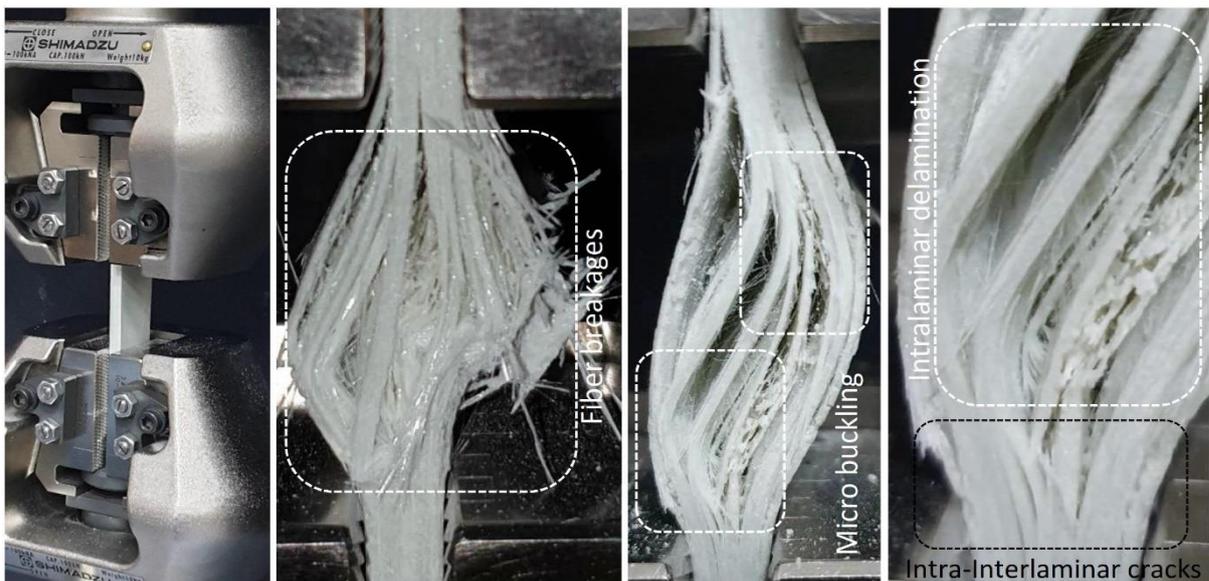


Fig. 10. Compressive failure in the longitudinal direction



Fig. 11. Compressive test failure in the transverse direction

5. CONCLUSION

In this present study, the mechanical behavior of the pultruded GFRP laminas in terms of tensile and compressive behaviors was examined in detail. For this purpose, tensile and compressive tests were carried out. The following conclusions can be drawn from this study:

✓ The tensile strength and elastic modulus of pultruded GFRP in the transverse direction are very low compared to that of the longitudinal direction. The average tensile strength is 290 MPa and elastic modulus are 23 GPa for the longitudinal and 40 MPa and 7 GPa for transverse direction of pultruded GFRP beam, respectively.

✓ In all tensile tests, it was observed that the damage started with micro-matrix cracks and showed progressive damage in the form of fiber rupture after the formation of delamination in the micro-layer.

✓ The compressive strength of pultruded GFRP in the transverse direction is low compared to that of the longitudinal direction. The average compressive strengths are 280 MPa and 85 MPa for the longitudinal and transverse direction of pultruded GFRP beam, respectively.

✓ The tensile and compressive stress of longitudinal direction are very similar. The ratio of tensile stress to compressive stress in the longitudinal direction is 1.04. However, the compressive stress is more than twice tensile stress in transverse direction. The ratio of compressive stress to tensile stress in the transverse direction is 2.13.

✓ It was observed that the damages in the compression tests proceeded very fast in the specimens and the final failure occurred as catastrophic damage.

✓ In the longitudinal direction specimens, the damage modes that occur after compression and tensile tests are intense; matrix cracks, in-layer delamination, micro-buckling, and fiber break.

✓ Damage modes in transverse direction specimens; matrix cracks, debonding, dense matrix damage and splitting damage at 45° angle.

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