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Experimental characterization of the fracture properties of pultruded GFRP structural elements

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Abstract

Pultruded Fiber Reinforced Polymers (FRPs) are a class of novel composite materials with remarkable strength (comparable or even greater to that of steel) and resistance to environmental effects. However, the strongly orthotropic behavior of these materials and the relatively high deformability and spatial variability in mechanical properties bring challenges to the widespread adoption of these elements in structural applications. To this end, the orientation and distribution of the fibers are the most influential parameters that affect both the ultimate strength and stiffness of the specimens. This work presents an experimental campaign conducted on GFRP specimens in uniaxial tension and 3-point bending; coupon specimens with three different fibers orientations (namely 0, 45, and 90 degrees) were tested to characterize the ultimate strength and failure modes Results of such experimental campaign are first presented, and detailed statistical measures of the so-obtained strength values are presented with the ultimate goal of characterizing the variability in mechanical properties in commercially available profiles.

Keywords: Fracture, Experimental Characterization, Fiber-Reinforced Polymers

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1. Introduction

In recent years, there has been an increasing interest in using pultruded Glass Fiber Reinforced Polymer (GFRP) composites in various engineering applications (Fig. 1) due to their high strength, corrosion resistance, and cost effectiveness. Pultrusion is a continuous manufacturing process that produces composite elements with constant cross-section by pulling fiber reinforcements through a resin matrix which is then polymerized in a heated die. The resulting composite materials have high fiber volume fractions and exhibit strongly orthotropic behavior, which make them suitable for various structural applications.

Fig. 1. Infrastructures and applications utilizing pultruded GFRP materials (Retrieved from Fibreline Composites Website 2009, https://www.cotswoldcanals.net/bonds-mill-bridge, and https://structurae.net/en/structures/lleida-footbridge).

Despite their many advantages, GFRP materials are known to exhibit high deformability in the direction orthogonal to the fibers alignment and relatively brittle failure, which limits their use and requires further investigation. GFRP composites are susceptible to various types of failure modes, including fiber breakage, interfacial debonding, matrix cracking, and delamination. These failures are often interrelated and depend on the material properties, loading conditions, and environmental factors. The fracture behaviour of GFRP materials is complex and can be influenced by various factors, such as fiber orientation, fiber volume fraction, resin type, curing conditions, and loading rate (Fascetti et al. 2021).

Several studies have investigated fracture in pultruded GFRP materials using various experimental and numerical techniques. For example, Karger-Kocsis et al. (2006) investigated the tensile and compressive behaviour of pultruded GFRP composites with different fiber orientations and found that the failure modes depend on the fiber orientation and loading direction. Lee et al. (2011) studied the interlaminar fracture toughness of pultruded GFRP laminates using double-cantilever beam (DCB) tests and concluded that the mode of failure was dominated by interfacial debonding between the plies. An experimental study by Li et al. (2019) investigated the effects of fiber orientation on the fracture toughness of pultruded GFRP composites. The results show that the fracture toughness increases with increasing fiber volume fraction and decreasing fiber orientation angle. Another critical factor that influences the fracture behaviour of pultruded GFRP composites is the matrix properties, which affect the composite's ability to transfer stresses between the fibers and prevent crack propagation. An investigation by Zhang et al. (2020) studied the fracture behaviour of pultruded GFRP composites with different matrix types, including epoxy and vinyl ester resins. The study found that the vinyl ester matrix showed superior fracture toughness and energy absorption capacity compared to the epoxy matrix.

Furthermore, the loading conditions applied to pultruded GFRP composites can also affect their fracture behaviour. For example, cyclic loading can lead to fatigue failure of the composite, while static loading can cause brittle fracture. A study by Cheng et al. (2017) investigated the fatigue behaviour of pultruded GFRP composites under different loading conditions. The results show that the composite's fatigue life is significantly affected by the loading frequency and stress level.

The mechanical behaviour of pultruded GFRP composites is highly dependent on their microstructure, fiber orientation, and matrix properties. In particular, the fracture behaviour of pultruded GFRP composites is a critical aspect that needs to be carefully evaluated to ensure their reliable and safe use in structural applications. Previous studies have shown that the fracture behaviour of pultruded GFRP composites is highly orthotropic, meaning that it varies significantly with the direction of applied load. The mode of fracture in pultruded GFRP composites is typically classified into two types: interlaminar and intralaminar. Interlaminar fractures occur between adjacent layers, while intralaminar fractures occur within a single layer. The mode of fracture is primarily determined by the fiber orientation and matrix properties (Cao et al., 2020). Researchers have extensively studied the fracture behaviour of pultruded GFRP composites using various experimental and numerical techniques. The experimental techniques include tensile, compressive, and bending tests, while the numerical techniques include finite element analysis (FEA) and cohesive zone modeling (CZM). These studies have shown that the fracture behaviour of pultruded GFRP composites can be significantly affected by the presence of defects such as voids, delamination, and cracks (Singh et al., 2019). These findings lead to the consideration that internal defects can induce significant spatial variability in material properties, which can ultimately lead to premature failure in area with lower fiber volume fractions (Zhu et al. 2020, Fascetti et al. 2018, and Feo et al. 2015). Several researchers have proposed models and theories to predict the ultimate behaviour of pultruded GFRP composites. These models and theories consider various factors such as fiber orientation, matrix properties, and the presence of defects. For example, the micromechanical models based on the mechanics of materials approach consider the composite as a continuum and predict the fracture behaviour using the stress-strain relationship. On the other hand, the fracture mechanics-based models consider the composite as a collection of discrete elements and predict the fracture behaviour using the energy release rate (Fiedler et al., 2018).

Experimental evidence shows that the transversely orthotropic behaviour of the material (and the relatively low strength and stiffness in the direction orthogonal to the fibers) can cause premature failures in pultruded composite structures. Web Flange Junctions (WFJs) can exhibit lower fiber contents as a result of the pultrusion process and accurate predictions of the ultimate strength of such areas are of crucial importance in the evaluation of the structural behaviour of structural assemblies.

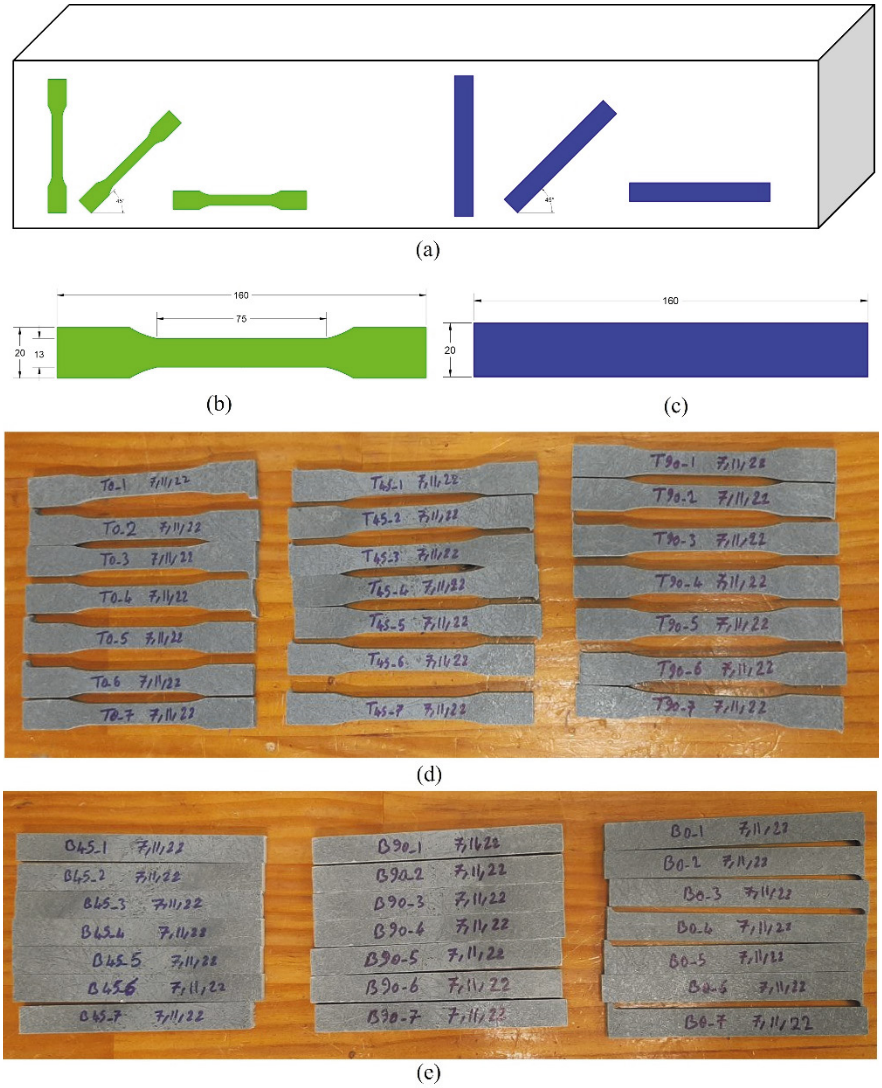
This paper aims to experimentally characterize the fracture behavior of pultruded GFRP elements by an experimental study and analytical investigation of the intended results. The major goal of study is to characterize the spatial variability of material properties along the length of the pultruded GFRP elements by selecting the elements from different locations from a hollow pultruded GFRP section and evaluating statistical dispersion of the experimental results.

2. Experimental Characterization

In order to investigate the experimental behavior of the pultruded GFRP sections, commercially available hollow square box elements produced by the Pultron manufacturing company were selected. Two types of tests were conducted: (i) Tensile and (ii) 3-point bending on coupon specimens obtained from the profiles. In order to study the effect of fiber orientation, three values for the orientation (i.e., 0°, 45°, and 90°) were selected.

Layout and geometry of the obtained specimens are reported in Fig. 2. In particular, Fig. 2a shows the cutting schedules of all specimens (which were obtained by means of a CNC machine), while Figs. 2b and 2c report the dimensions of the two specimen types (the thickness of all specimens was 7 (mm)). Finally, Fig. 2d illustrates the specimens used in the tensile tests, while Fig. 2e shows the specimens used for the 3-point bending tests.

Both tensile (following ASTM D3916) and 3-point bending (following ASTM D8069) tests were executed for three different fiber-load orientations, with 7 specimens tested for each orientation. Therefore, a total of 21 specimens were tested for each type of test. The experimental campaign was conducted in the material characterization laboratory at the University of Waikato. An Instron (6800 series) press with capacity 100kN was used in the execution of all the presented tests.



(a)

(b)

(c)

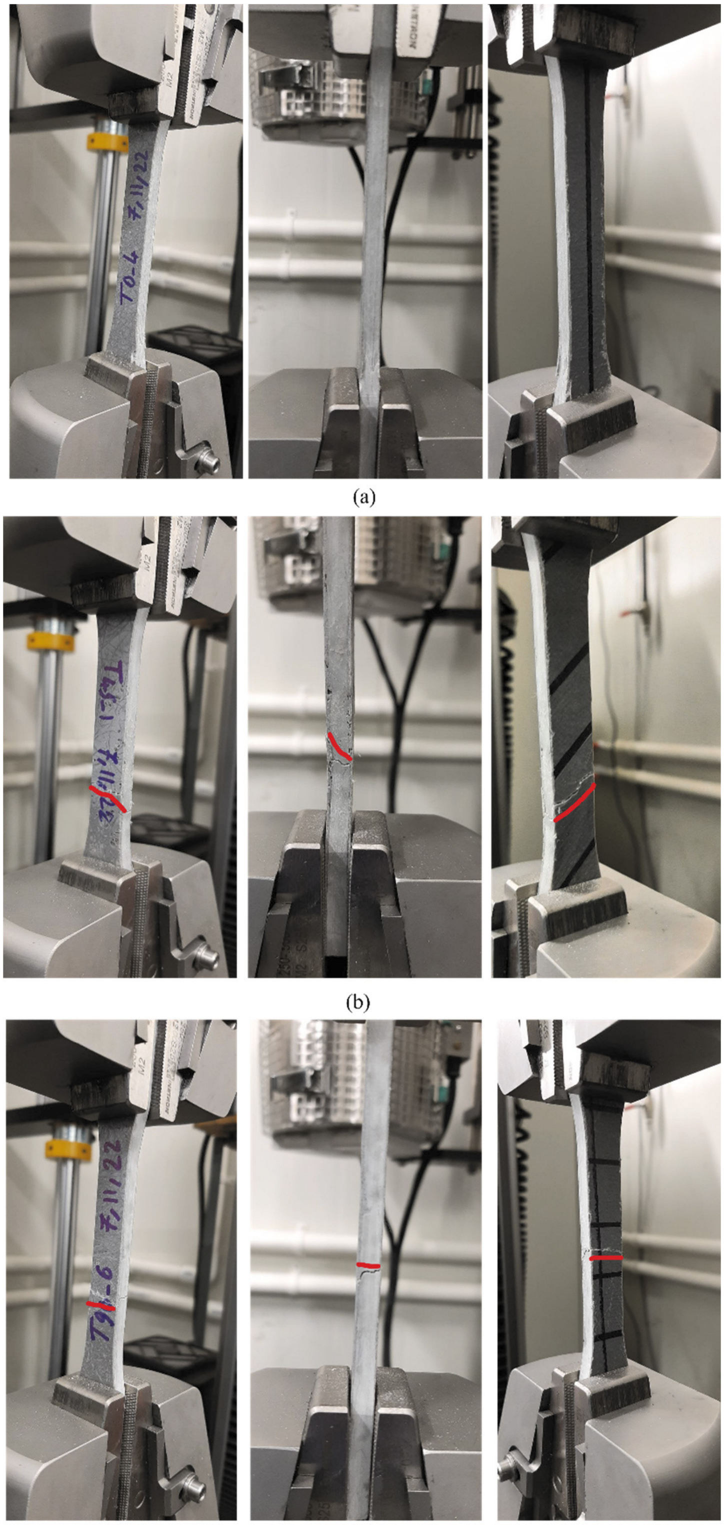
(d)

(e)

Fig. 2. (a) Hollow section of pultruded GFRP section and cut plan, (b) dimensions of tensile specimens, (c) dimensions of 3-point bending specimens, (d) tensile specimens, and (e) 3-point bending specimens.

2.1. Tensile Tests

Tensile tests were conducted for three different fiber-load orientations and the obtained failure modes are reported in Fig. 3. As it can be observed, 0-degree specimens exhibit little to no damage from on the outer surfaces of the specimens, as a result of the fact that failure occurs by means of fiber breakage along the loading direction (see Fig. 3a). Conversely, the observed crack paths for the 45-degree orientation exhibit preferential orientations on planes parallel to the direction of the fibers (see Fig. 3b). Lastly, Figure 3c illustrates the crack failure modes observed in the 90-degree orientation tests; matrix failure is observed with ultimate strength mainly governed by the strength of the polymeric matrix.



(a)

(b)

(c)

Fig. 3. Tensile test failure patterns for different orientations (a) 0-degree, (b) 45-degree, and (c) 90-degree.

2.2. Three-point Bending Tests

Figure 4 reports the failure modes observed during the 3-point bending tests for 0, 45, and 90 degrees orientations, respectively. In particular, failure in 0-degree specimens initiate at the bottom of the coupon specimens, with little to no damage observed in the top portion. Figure 4b reports the failure patterns observed for the 45-degree orientation specimens; diagonal cracks were observed in all specimens on planes parallel to the fiber orientation. Conversely, the 0-degree specimens exhibit failure on direction parallel to the main bending axis, as observed in Fig 4c.

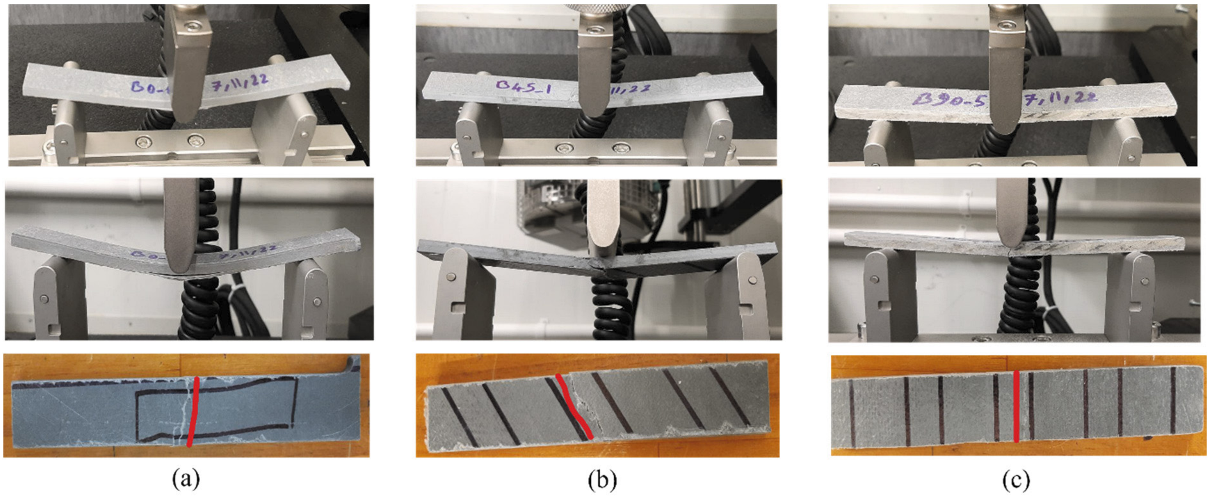


Fig. 4. 3-point bending test failure and crack paths for different orientations (a) 0-degree, (b) 45-degree, and (c) 90-degree

3. Analytical Investigation on Fracture Behaviour

Many studies have been proposed in literature to characterize the fracture behaviour of pultruded GFRP. The vast majority of such studies focused on characterizing the macroscopic behaviour of GFRP in terms of stress and strain responses. In this study, the fracture behaviour of pultruded GFRP is analysed through a comprehensive experimental analysis. The results show that the failure mode of pultruded GFRP is governed by fiber breakage in 0-degree, mixed fiber-matrix failure in the 45-degree, and interlaminar failure in 90-degree specimens, respectively.

3.1. Fracture Properties

To this end, the effect of geometrical and structural parameters on the fracture of pultruded GFRP was also studied as below.

$$Y = 1.12 - 0.23\left(\frac{a}{W}\right) + 10.55\left(\frac{a}{W}\right)^2 - 21.71\left(\frac{a}{W}\right)^3 + 30.82\left(\frac{a}{W}\right)^4 - 31.92\left(\frac{a}{W}\right)^5 + 22.69\left(\frac{a}{W}\right)^6 - 10.37\left(\frac{a}{W}\right)^7 + 2.39\left(\frac{a}{W}\right)^8 \quad (1)$$

Newman and Raju (1981) proposed the use Eq. (1) to obtain the geometric factor (Y) for FRP materials, where a is the crack length and W is specimen's width. In order to evaluate the fracture toughness (K_{IC}), Eq. (2) was used based on work by Hou and Niu (2013) for FRP materials:

$$K_{Ic} = 1.1\sigma_f \times \sqrt{(\pi \times a)} \quad (2)$$

$$K_I = Y\sqrt{\pi} \times K_{Ic} \quad (3)$$

$$G_{IC} = {K_{Ic}}^{2} \,/\, E \tag{4}$$

Where, σ_f is the ultimate tensile strength, and E is the modulus of elasticity.

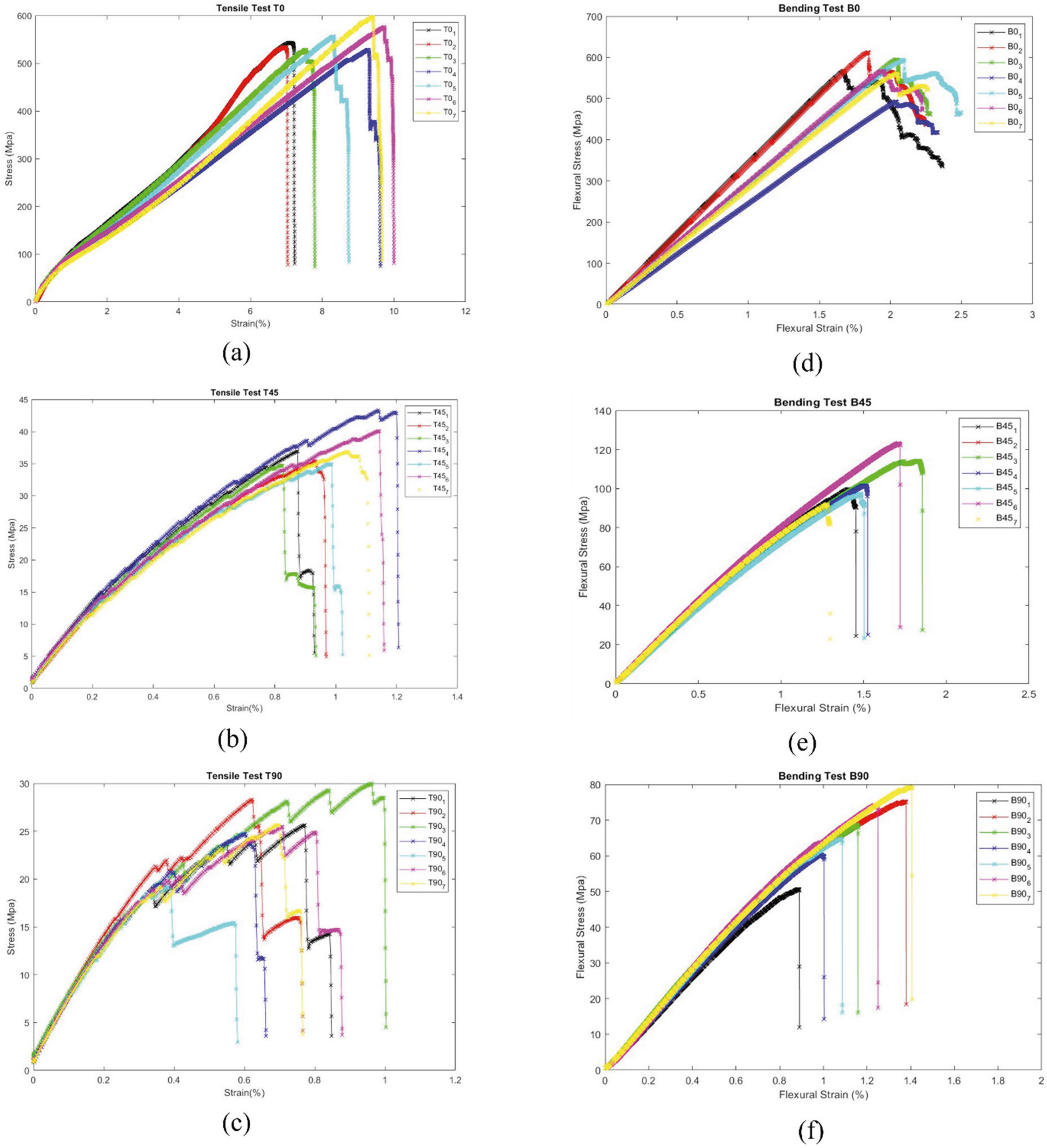
Stress intensity factor (K_I) and Energy release rate (G_{IC}) were obtained by means of Eqs. 3 and 4 (Rie and Liebowitz (1988) and Irwin (1957)). All the obtained Results are reported in Table 1.

Table 1. Experimentally obtained fracture properties.

	Tensile Test			3-point Bending		
Mechanical Properties	0-degree	45-degree	90-degree	0-degree	45-degree	90-degree
Ultimate Strength (MPa)	547.18	36.82	25.94	576.89	105.33	68.59
Ultimate Strain (%)	8.61	1.04	0.78	2.30	1.61	1.17
$K_{Ic}\ (MPa\sqrt{m})$	601.90	40.50	28.54	634.58	115.86	75.45
$K_{I}\ (MPa\sqrt{m})$	40501	2724	1923	42705	7797	5077
$G_{IC}\ \left(\frac{N}{m}\right)$	57.01	0.46	0.24	16.06	2.05	0.97

3.2 Statistical Analysis

The stress-strain curves obtained for all the 42 specimens tested in the experimental campaign are reported in Figs. 6a-f. As it can be observed, relatively brittle failure was observed in most specimens, and a significant variability in ultimate strength and corresponding strain was observed in all the tests. To this end, a statistical analysis was performed, to better characterize the observed spatial variability. Normalized peak stress (Fig. 5a) and corresponding strain (Fig. 5b) are analyzed for all tests in order to observe the data dispersion based on median values. As it can be observed, experimental results show that a relatively higher degree of variability is observed for both the 45- and 90-degree orientation tests, highlighting how zones with lower fiber contents might lead to premature failure of the structural elements. This finding is in good agreement with previous findings from other authors (Feo et al. 2015 and Mosallam et al. 2017).



(a)

(d)

(b)

(e)

(c)

(f)

Fig. 5. Stress-Strain curves obtained from (a) 0-degree rensile, (b) 45-degree tensile, (c) 90-degree tensile, (d) 0-degree 3-point bending, € 45-degree 3-point bending, (f) 90-degree 3-point bending tests, respectively.

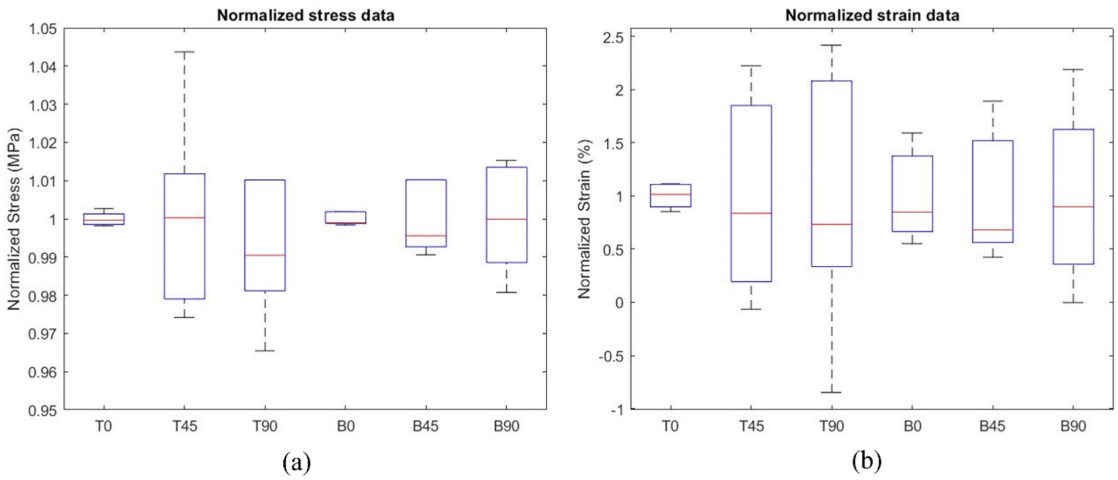


Fig. 6. Normalized ultimate stress (a) and corresponding strain (b).

The experimental results (in terms of median values) are also collected in Fig. 7 together with derived Tsai-Hill failure criteria (Tsai and Hill, 1965) curves for both tensile and 3- point bending tests. Results show that an an acceptable agreement is obtained in the comparison.

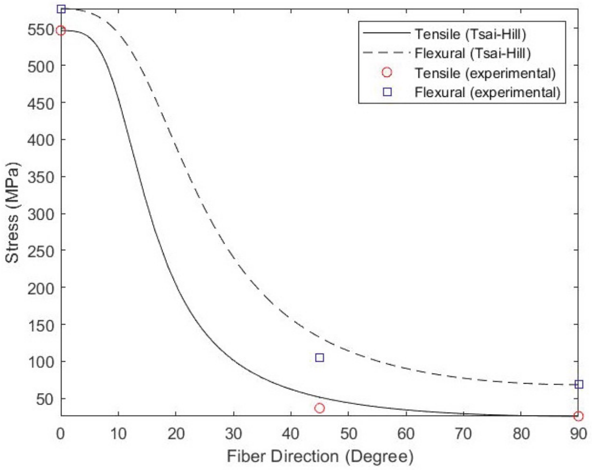


Fig. 7. Stress vs. fiber orientation

Conclusions

Pultruded GFRP materials are newly developed alternative materials in civil engineering applications. The strongly orthotropic behavior and relatively high deformability in the direction orthogonal to the fibers, however, are sources of concerns in practice and require extensive characterization to provide guidelines for the use of GFRP elements in structural application. To this end, this study presented an experimental campaign performed on Pultruded GFRP elements obtained from commercially available pultruded specimens. An analytical study on the fracture behavior of the material was conducted, based on the results obtained in the experimental campaign. Statistical characterization of the experimental results also demonstrated that a higher degree of variability is observed for higher values of the load-to-fiber orientation.

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