

Evaluating mechanical efficiency of glass fibres in a polymer profile

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ABSTRACT

This study focuses on the mechanical performance of pultruded glass fibre-reinforced polymer (GFRP) profiles developed for structural applications. Fibre content determines the tensile resistance of such components, and technical specifications describe this essential parameter. However, it does not determine the actual reinforcement efficiency. This manuscript illustrates the above inference both experimentally and analytically, investigating a GFRP square hollow section (SHS) profile available at the market. Standard tensile coupon test defines the material characteristics; a three-point-bending test determines the mechanical performance of the profile. A digital image correlation system captures deformations and failure mechanism of the SHS bending specimen. The developed finite element model with smeared reinforcement estimates the efficiency of the glass filaments, i.e. the ability to predict the actual mechanical resistance (flexural stiffness) under the assumption of the experimentally determined elasticity modulus of bare fibres. Scanning electron microscopy relates the composite microstructure and mechanical performance of the selected profile.

1. Introduction

Current industrial trends revealed that the application of innovative engineering technologies requires new design concepts related to developing materials with mechanical properties tailored for construction purposes [1]. Fibre-reinforced polymer (FRP) materials, in general, and glass fibre-reinforced polymer (GFRP) pultruded profiles, especial, represent a promising alternative to metal because of their light-weight, electromagnetic transparency, and excellent corrosion and fatigue resistance [2,3]. The GFRP profiles' production is also possible in a large volume at low operating costs, high production rate, high fibre content, product reproducibility, and engineering tolerances [4].

The pultrusion technology is a well-developed method of producing advanced composite parts, distribution continuous mechanically resistant filaments in a polymer matrix that protects the fibre reinforcements from the unfavourable environment [5]. The filament distribution controls the mechanical properties of pultruded components and their degradation under harsh environmental conditions [3,4,6–9]. However, the fibre content does not determine the actual reinforcement efficiency.

This manuscript illustrates it both experimentally and analytically, investigating a GFRP square hollow section (SHS) profile available at the market. The SHS elements are widely used in various structural applications because of their high torsional resistance and aesthetic appearance [10,11].

A digital image correlation (DIC) technique is efficient in verifying deformation homogeneity in polymeric materials [12,13] and localising strain concentrations in structural components [11,14]. This study employs DIC technologies for capturing deformations and failure mechanism of the GFRP profiles during the mechanical tests.

A numerical modelling approach determines the filaments' efficiency reinforcing the polymer, comparing the simulated outcomes with the test results. The typical numerical models assume FRP material structure homogeneous, making no distinction between the polymer and filament materials [15–18]. Thus, the anisotropic material characteristics' determination becomes depending on empirical relationships. On the contrary, this study employs the smeared reinforcement model initially developed for concrete structures [19]. Following this modelling concept, the 1D reinforcement is uniformly spread inside the solid

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body, enabling separate material models for glass filaments and polymer matrix. The constitutive models assume the material characteristics described in the manufacturer datasheet.

This study proposes the equivalent reinforcement ratio to measure the actual reinforcement effect. The proposed concept employs the effective reinforcement idea implemented in the design code “Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings” for reinforced concrete structures. It is also in line with the experimental findings [20–22]. In this study, the reinforcement efficiency is understood as its ability to ensure the actual mechanical resistance (stiffness) under the assumption of the given elasticity modulus of the bare filaments. The scanning electron microscopy (SEM) technique relates the reinforced polymer structure and the composite mechanical performance.

2. Mechanical tests

Locally produced SHS pultruded GFRP profiles (UGIRA, Lithuania) represent the research object. Vinylester resin and E-glass continuous filaments compose the profile; the fibre mass percentage w_f specified by the producer is equal to 75%. Standard tension coupon tests determine the material properties. A three-point-bending tests define the structural performance of the profile.

2.1. Material properties

The manufacturer datasheet describes the characteristics of the GFRP constituents. Table 1 presents the material properties.

The tensile coupon tests were carried out by following the ASTM D 3039/D 3039M – 17 “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials” standard requirements. The mechanical properties, i.e. the tensile strength and elasticity modulus, were determined in the pultrusion direction, corresponding to the filament orientation. As shown in Fig. 1a, all coupons were tested using a 250 kN capacity servo-hydraulic machine Z250 (Zwick, Germany). Four coupons were tested. Fig. 1b shows the obtained stress-strain diagrams. Linear elastic behaviour is characteristic of coupon behaviour. Table 2 summarises these results.

2.2. Flexural tests

Mechanical properties of GFRP profiles are irregular within the cross-section due to the material heterogeneity and anisotropy [3,23]. Complex stress-strain behaviour is also characteristic of flexural specimens because of the tensile and compressive material properties’ distinction [17] and stress localisation effects [9,16]. Hence, three-point-bending tests were carried out to evaluate the mechanical performance of the structural profiles. Five pultruded GFRP SHS profiles with the compact $40 \times 40 \times 3.2$ mm (height $\times$ width $\times$ thickness) cross-section were tested until failure. This geometry choice ensures minimising the web-crippling problems [9]. The test samples had a length of 1000 mm. Steel rollers and bearing steel plates were placed over the supports, protecting the profile from the local failure. Fig. 2 shows the loading scheme and testing setup.

The profiles were loaded by a 5 MN capacity servo-hydraulic machine LFW 5000 (W+B, Switzerland) in the displacement control manner.

Table 1
Material properties of GFRP composite constituents.

Property	Material	
	Vinylester resin	E-glass fibre (filament)
Tensile strength [MPa]	85	3400
Elasticity modulus [GPa]	3.3	70.2
Poisson’s ratio	0.324	–
Density [g/cm ³]	1.7	2.55

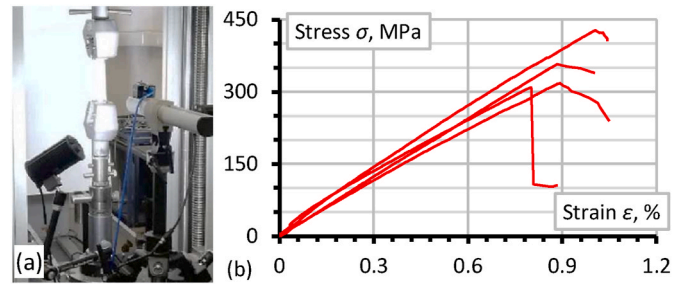


Fig. 1. Tension coupon tests: (a) testing machine Zwick Z250; (b) stress-strain diagram.

Table 2

Mechanical properties of the pultruded GFRP material.

Property	Value
Tensile strength [MPa]	353.1 ± 54.0
Elasticity modulus [GPa]	38.90 ± 3.06
Poisson’s ratio	0.362 ± 0.017

A 100 kN capacity load cell monitored the load; a digital image correlation (DIC) system captured surface deformation of the profiles; paired 100 mm range and 0.01 mm precision linear variable displacement transducers (LVDT) monitored vertical displacements at the mid-span. An ALMEMO 2890-9 data logger acquired the test data every second.

Fig. 3 shows the average vertical displacements measured by paired LVDT located at the profile mid-span (Fig. 2a). The load-displacement diagrams of all specimens (G1–G5) demonstrate elastic behaviour characteristic of the bending profiles. The samples also revealed similar flexural stiffness and failure mechanism—crushing of the compressive zone followed with the cross-section integrity loss was characteristic of all beams. Fig. 4 shows the typical failure cases.

With the aid of the DAVIS 8.1.6 software package by LAMISON, the DIC system was used to monitor surface strain at the rate of one image per 500 N. Fig. 2b shows the digital cameras’ stereoscopic layout. This equipment enables capturing relative displacement of the pixels identified at the monitoring surface covered with the contrast spray pattern, facilitating the software tracking of the movement tensors of the surface pixels. The DIC technique enables monitoring relative displacements of any points, which can be arbitrarily set on the surface at the image processing stage after the physical tests [11].

3. Numerical modelling

3.1. Finite element model

The numerical modelling estimates the glass filament efficiency to reinforce polymeric profiles. The bending test is the modelling object. Numerical simulations have been carried out using commercial finite element (FE) software ATENA [19]. The deformation problem was solved in a 3D formulation applying the Newton-Raphson iteration procedure. Fig. 5 shows the numerical model built up using 3D hexahedral solid finite elements. A regular FE mesh with an average size of 3 mm was used. Steel plates were modelled to avoid stress concentration at the supports and the load application point. The boundary and loading conditions shown in Fig. 5a represent the physical tests (Fig. 3a).

The profile was modelled using the experimentally obtained material properties and geometrical parameters. Thus, the model (Fig. 5b) represents the initial geometry imperfection (relative rotation of the internal rectangular shape of the cross-section) of the test specimen (Fig. 5c).

The 3D solid finite elements describe the polymer matrix. Smeared reinforcement represents the glass filaments. Fig. 6 sketches this

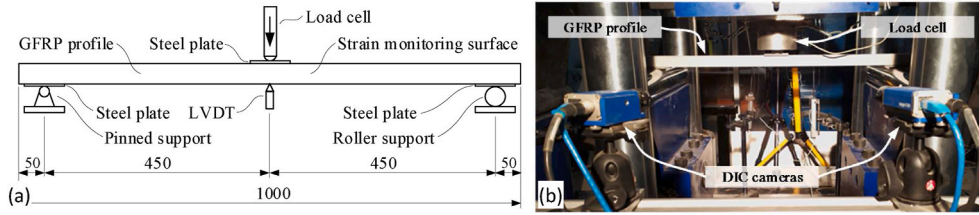


Fig. 2. Three-point bending test: (a) loading scheme (units [mm]); (b) testing setup.

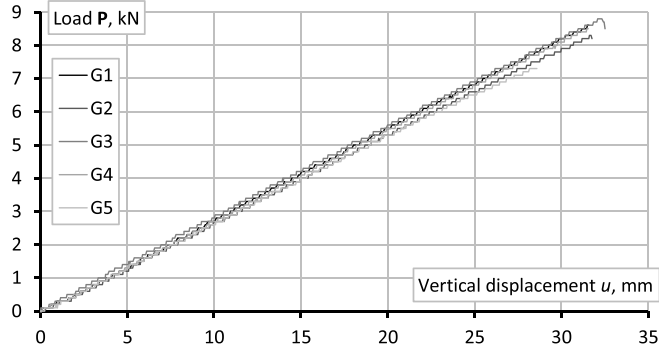


Fig. 3. Load-vertical displacement relationships at the mid-span of all beam specimens.

modelling concept. In such a way, the reinforcement is considered as an internal component of the composite material, having a separate 1D material model. The reinforcement and pultrusion directions coincide.

Three FE simulations were carried out assuming different filament volume fraction. The following section describes the filament quantification principles. The material parameters listed in Table 1 describe constitutive models of the vinyl ester resin and smeared reinforcement in all simulations. The vertical displacement was applied in small increments (0.3 mm) until the load-bearing capacity was exceeded. Fig. 7 compares the numerical prediction and test results.

3.2. The equivalent filament concept

As mentioned in the previous section, three FE models (Fig. 8) assume different volume contents of filaments. Model 1 accepts the volume percentage $V_f = 66.7\%$. That content corresponds to the mass percentage w_f specified by the producers. The following expression relates the volume V_f and mass w_f percentages:

$$V_f = w_f \cdot \left[\rho_f \cdot \left(\frac{w_f}{\rho_f} + \frac{1 - w_f}{\rho_m} \right) \right]^{-1}, \quad (1)$$

where ρ_f and ρ_m are the fibre and matrix densities (Table 1).

The tensile coupon test determines the deformation behaviour of Model 2. Following the load-sharing concept [24], the external load P induces two internal forces acting on polymer matrix N_m and glass filaments N_f :

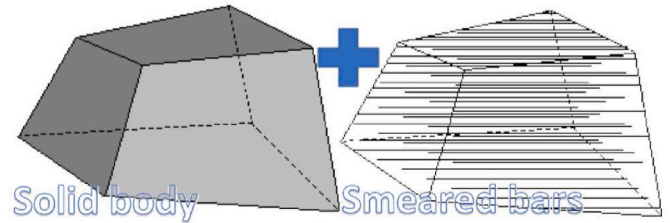


Fig. 6. The smeared reinforcement concept [19].



Fig. 4. The bending specimens' failure.

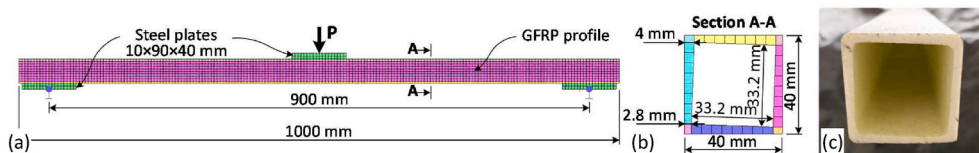


Fig. 5. Flexural GFRP profile: (a) numerical model; (b) modelled cross-section; (c) actual cross-section.

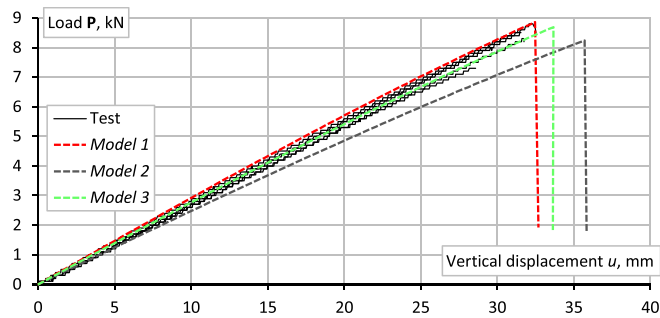


Fig. 7. Experimental and simulated load-vertical displacement diagrams.

$$\mathbf{P} = \mathbf{N}_m + \mathbf{N}_f. \quad (2)$$

The above forces can be expressed in the average axial strain terms:

$$E_c \cdot A_c \cdot \varepsilon_c = E_m \cdot A_m \cdot \varepsilon_m + E_f \cdot A_f \cdot \varepsilon_f, \quad (3)$$

where E , A , and ε are the elasticity modulus, area, and average axial strain; the indexes c , m , and f correspond to the GFRP composite, polymer matrix, and glass filaments. The *Navier-Bernoulli* hypothesis (the strain profile within a cross-section is represented as a plane) assumes equality of all average strains, simplifying equation (2). The filament reinforcement ratio V_f describes the relationship between the areas A in formula (2), as follows

$$E_c \cdot A_c = E_m \cdot A_c \cdot (1 - V_f) + E_f \cdot A_c \cdot V_f. \quad (4)$$

The solution of equation (4) describes the equivalent reinforcement ratio $V_{f,eq}$ under the assumption of the experimental value of the composite coupon elasticity modulus $E_{c,exp}$:

$$V_{f,eq} = (E_{c,exp} - E_m) / (E_f - E_m). \quad (5)$$

The elasticity moduli described in [Tables 1 and 2](#) determine the equivalent volume percentage $V_{f,eq} = 53.2\%$ assumed in *Model 2*. The calculated volume is well below the predefined rate of 66.7% (calculated from the declared mass fraction of 75%). [Fig. 7](#) demonstrates the inadequacy of the equivalent volume fraction determined from the tensile coupon tests for predicting the deformation behaviour of the bending

SHS GFRP profile.

Thus, the equivalent volume content $V_{f,eq} = 62.0\%$ assumed in *Model 3* was tailored to adequately represent the GFRP profile's deformation behaviour (Fig. 7). Still, this fibre content does not reach the reference value of 66.7% (assumed in *Model 1*). Section 4 relates the mechanical performance of the GFRP SHS beam to the internal structure of the fibre-reinforced polymer.

3.3. The numerical model verification

The FE model verification employs the methodology described in Ref. [11] when the local deformations predicted by *Model 3* are compared with the DIC analysis results. The DIC systems' ability to identify relative displacements of any pixels of digital images makes the deformation analysis of critical zones identified during the tests possible. In this study, the DIC system (Fig. 2b) estimated local strains near the steel plate edge, using the 10 mm virtual strain gauges, as shown in Fig. 8a. The *Model 3* predictions are defined at the virtual gauge location (Fig. 8b).

Fig. 9a shows the strain distribution over the profile height identified by the DIC system capable of monitoring deformations of the flat vertical surface only (coloured areas in Fig. 9). Therefore, the diagrams given in Fig. 9a do not reach the top and bottom boundaries of the profile. The unidentified zones correspond to the rounded corners of the SHS profile (Fig. 5c). The FE model did not simulate the roundness of the corners (Fig. 5b). The diagrams are related to the external load $\mathbf{P}$.

Remarkably, the *Navier-Bernoulli* hypothesis (a plane represents the strain profile within a cross-section) is not valid in the SHS GFRP beam at already low loading levels (e.g., 3 kN, Fig. 9a). That is the synergetic consequence of the tensile and compressive elasticity modulus distinction [17] because of the slender filaments' inability to resist compressive stresses efficiently and the top flange local buckling effect characteristic of SHS flexural profiles [11].

The DIC results comparison with numerical simulation (Fig. 9b) proves the above inference—*Model 3* correctly represents the compressive strain increase whilst the smeared reinforcement does not resist compression [19]. The comparative analysis of these diagrams proves sufficient adequacy of the *Model 3* predicting non-linear deformation behaviour of the GFRP composite profile. In most cases, the differences between the tensile strains calculated using FE and estimated by the DIC

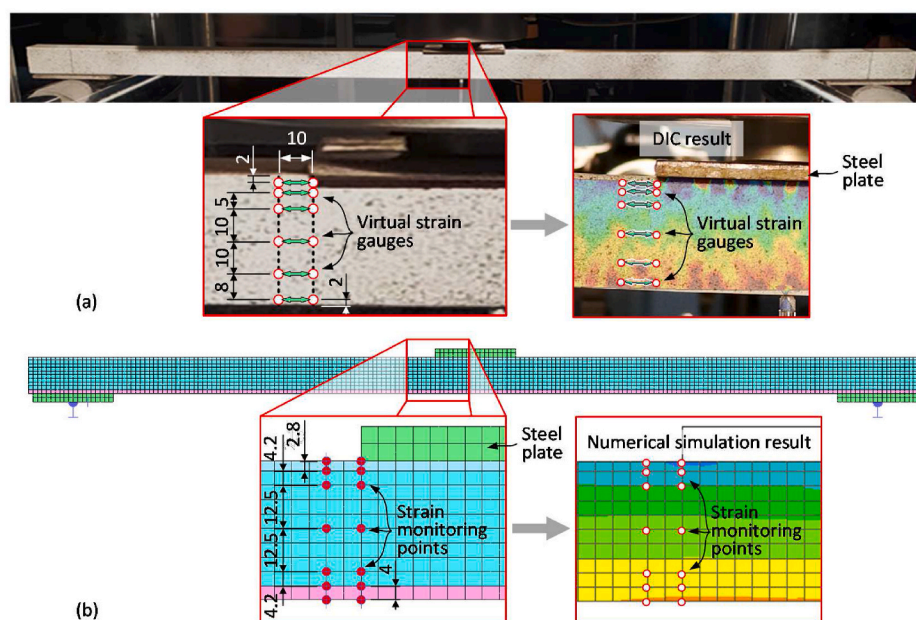


Fig. 8. Local strain measurement: (a) digital image correlation system; (b) finite element analysis.

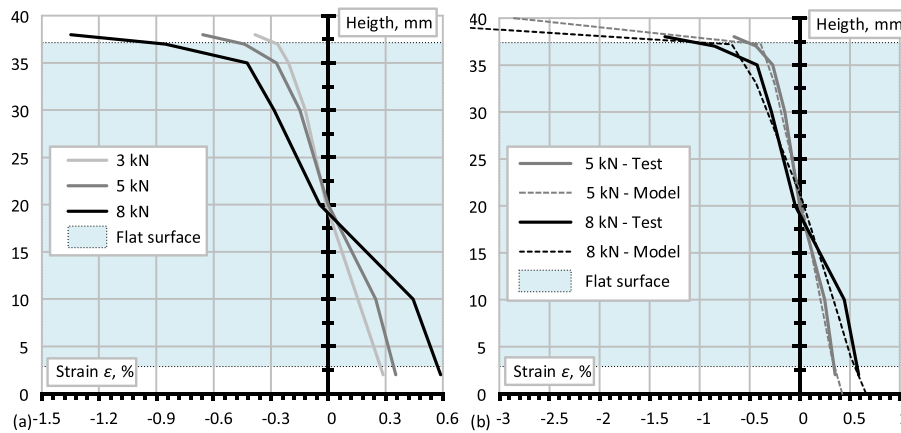


Fig. 9. Local strains in the profile: (a) digital image correlation results; (b) finite element analysis.

system do not exceed 10%; the maximum strain differences reach 50% (near the neutral axis); the average differences of the strains do not exceed 15%. Failure of the compressive zone governs the predicted ultimate load (Fig. 7). That agrees with the results shown in Fig. 4 and the literature findings [2,9,10,12,14].

4. Analysis of internal structure of GFRP composite

4.1. Quantification of the filament fraction

The filaments' content was estimated experimentally by following ISO 1172:1996 "Textile-glass-reinforced plastics — Prepregs, moulding compounds and laminates — Determination of the textile-glass and mineral-filler content — Calcination methods" standard requirements using an electric furnace SNOL February 7, 1100 (SNOL, Lithuania). For this purpose, small fragments (≈ 10 g), cut from the webs and corners of the profiles, were dried until the constant weight at 105 ± 5 °C (the drying time = 24 h). After that, the specimens were heated at 625 ± 5 °C until the polymer evaporated. The heating regime: 2 h – to reach a temperature of 625 °C and 3 h – to a constant weight. The heating procedure determines the mass percentage of fibres w_f and Equation (1) describes the volume fraction V_f . This test gets only an approximate estimate of w_f because of neglecting the heat-resistant aggregates' effect [3,7].

Fig. 10 shows the analysis results of three (#1–#3) web and corner samples. This figure demonstrates almost identical fibre content in all specimens. That means that the current pultrusion technologies solved the resin localisation problems at the web-flange junction identified previously [15,25]. The average volume fraction is equal to 67.8% (Fig. 10) and well agrees with the V_f value assumed in Model 1 (Section

3.2). Still, the observed fibre content exceeds the equivalent fraction $V_{f,eq} = 62.0\%$ taken in Model 3. Therefore, the following sub-section investigates the microstructure of the GFRP profiles.

4.2. Microstructure analysis

Scanning electron microscopy (SEM) is used to investigate the separate fibres and the GFRP composite microstructure. A field emission scanning electron microscope JSM-7600F (JEOL, Japan) was used for that purpose. The parameters of the SEM tests were as follows: 10 kV voltage, 11–13 mm distance to the specimen surface, and magnification varying from $\times 100$ to $\times 2000$. The web and corner samples were prepared by abrasive grinding. After that, the specimens were covered with an electrically conductive thin Au layer by evaporating an Au electrode in a vacuum using a Quorum Q150R ES equipment (QUORUM, UK).

Fig. 11 shows the microstructure of fibres from the heating tests (Section 4.1). This figure compares the images with the similar test results of the FIBERLINE (Denmark) samples [26]. The difference in diameter is the centre outcome of these pictures—the reference fibres' diameter varies from 32 μm to 38 μm ; the FIBERLINE samples go in the 16–22 μm range. The diameter increase (regarding FIBERLINE filaments) can also cause the decrease in the reinforcement efficiency observed in Model 1 and Model 3 (Fig. 7). The results observed in the reinforced concrete specimens [20–22] support the above inference—distribution of the same reinforcement area in a higher number of bars (of smaller diameter) can noticeably increase the stiffness of composite elements. Thus, the fibre diameter reduction for the same volumetric content could increase the reinforcement efficiency.

The SEM analysis (Fig. 11) also shows that the reference samples' surface is smooth. On the contrary, the FIBERLINE fibres have uneven rough surfaces with small particles with an approximate size of 1–3 μm that could potentially improve adhesion of the fibres and polymer matrix.

Figs. 12 and 13 show the microstructure of the web and corner specimens. Independently on the sample location, the contact zone between the fibre and the matrix is dense (see zones marked by white rectangular in Figs. 12b and 13b). Most probably, the cutting during the SEM samples preparation induces the observed defects at the fibre and matrix interaction zone. Still, the filament absence observed in Fig. 13a is the technological flaw result. Such defects could cause the reduction of the equivalent fraction $V_{f,eq}$ observed in Section 3.2.

Fig. 14 shows the view on the cut surface corresponding to the pultrusion direction. Numerous damaged filaments result from such a cut. Remarkably, similar surfaces determine the boundaries of the coupon samples used for defining the equivalent fraction $V_{f,eq}$ in Model 2 (Section 3.2). The fibre damages at the side surfaces could explain the reinforcing efficiency losses observed in tensile samples (compare $V_{f,eq}$

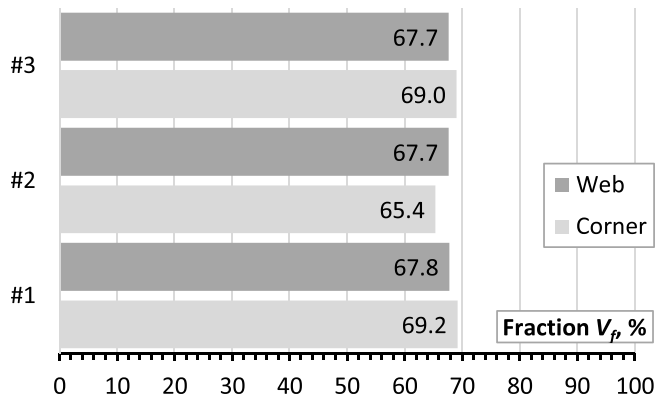


Fig. 10. Estimated volumetric fibre fraction.

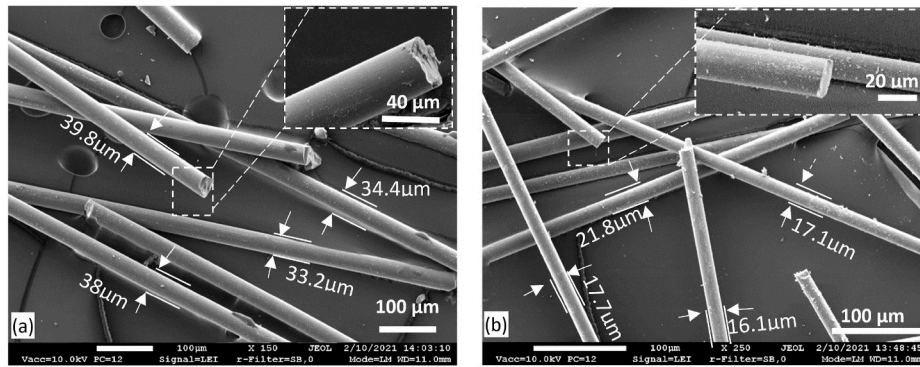


Fig. 11. Microstructure of separate fibres [26]: (a) reference material; (b) FIBERLINE fibres.

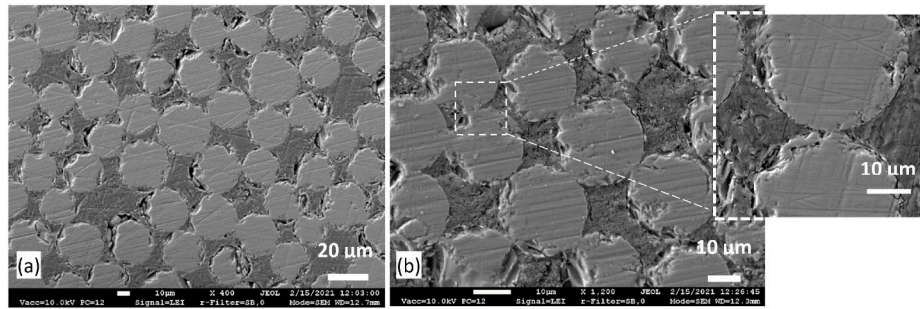


Fig. 12. Microstructure of the web zones of various magnification: (a) $\times 400$; (b) $\times 1000$.

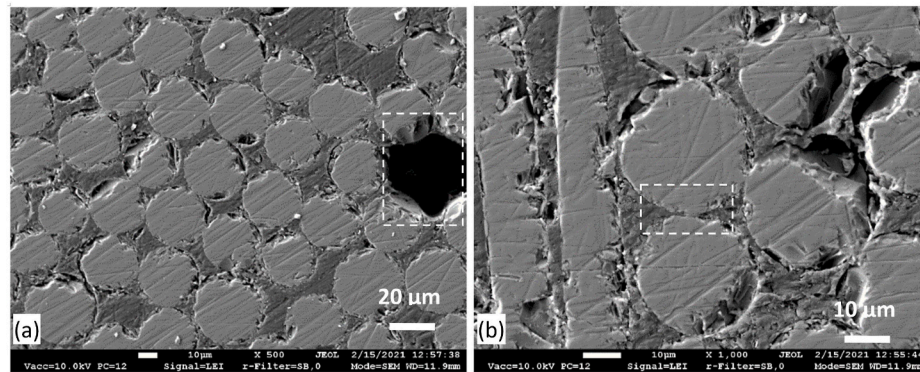


Fig. 13. Microstructure of the corner zones of various magnification: (a) $\times 500$; (b) $\times 1000$.

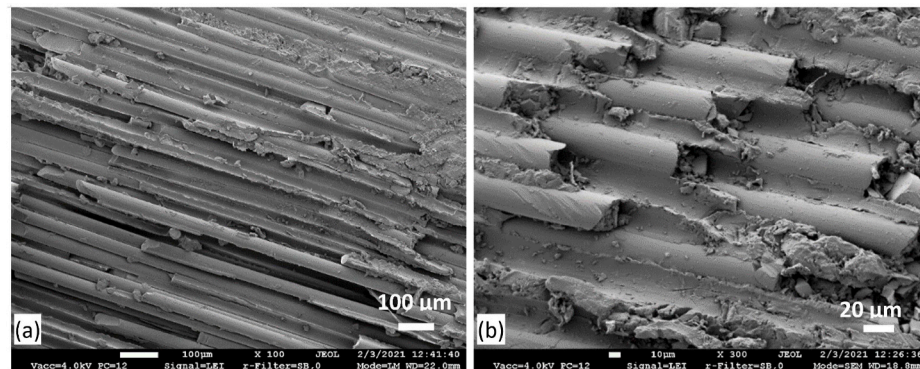


Fig. 14. Web microstructure consistent with pultrusion direction: (a) $\times 100$ and (b) $\times 300$ magnifications.

of *Model 2* and *Model 3*). This unfavourable effect could increase with the decrease of the sample size, i.e. the increase of the cut area regarding the sample cross-section. Thus, the tensile coupons are not suitable for determining the equivalent fibre content for the FE simulation of GFRP flexural elements.

5. Conclusions

This study focuses on the mechanical performance of pultruded glass fibre-reinforced polymer (GFRP) profiles developed for structural applications. It proposes the equivalent reinforcement ratio to measure the actual reinforcing effect. The following conclusions are made from this investigation:

- The finite element (FE) approach, employed the equivalent fibre fraction and smeared reinforcement concepts, is suitable for estimating the reinforcement efficiency when experimentally obtained material parameters describe constitutive models of the glass filaments and polymer matrix.
- The fibre content does not describe the reinforcement efficiency in the GFRP square hollow section profile available at the market. On average, the actual efficiency of glass fibres is 7% lower than expected from the manufacturer declared mass fraction content.
- Scanning electron microscopy technique determined a possible improvement way of the selected profile mechanical performance. The reduction of the filament diameter for the same fibre content could potentially increase the reinforcement efficiency.
- The standard coupon tensile tests are not suitable to determine the equivalent reinforcement ratio for the FE simulation of GFRP flexural elements.

Credit authorship contribution statement

Viktor Gribniak – Conceptualization; Supervision; Funding acquisition; Writing – Final correction.

Arvydas Rimkus – Methodology; Software; Visualization; Project administration; Writing – Draft version.

Linus Plioplys – Software; Visualization; Data curation; Investigation.

Ieva Misiūnaitė – Formal analysis; Validation; Writing – Final correction.

Renata Boris – Methodology; Data curation; Investigation.

Tautvydas Pravilonis – Resources; Data curation; Investigation.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical limitations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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