

RESEARCH ARTICLE

The development of nature-inspired gripping system of a flat CFRP strip for stress-ribbon structural layout

Viktor Gribniak ^{1,2,*}, Aleksandr K. Arnautov ^{3,4} and Arvydas Rimkus ^{1,2,3}

¹Laboratory of Innovative Building Structures, Vilnius Gediminas Technical University, Sauletiškio av. 11, Vilnius LT-10223, Lithuania; ²Department of Steel and Composite Structures, Vilnius Gediminas Technical University, Sauletiškio av. 11, Vilnius LT-10223, Lithuania; ³Institute of Building Materials, Vilnius Gediminas Technical University, Linkmenų str. 28, Vilnius LT-08217, Lithuania and ⁴Institute for Mechanics of Materials, University of Latvia, Aizkraukles str. 23, Riga LV-1006, Latvia

*Corresponding author. E-mail: Viktor.Gribniak@vilniustech.lt  <http://orcid.org/0000-0001-8296-0037>

Abstract

The elegant stress-ribbon systems are efficient in pedestrian bridges and long-span roofs. Numerous studies defined corrosion of the steel ribbons as the main drawback of these structures. Unidirectional carbon fiber-reinforced polymer (CFRP) is a promising alternative to steel because of lightweight, high strength, and excellent corrosion and fatigue resistance. However, the application of CFRP materials faced severe problems due to the construction of the anchorage joints, which must resist tremendous axial forces acting in the stress-ribbons. Conventional techniques, suitable for the typical design of the strips made from anisotropic material such as steel, are not useful for CFRP strips. The anisotropy of CFRP makes it vulnerable to loading in a direction perpendicular to the fibers, shear failure of the matrix, and local stress concentrations. This manuscript proposes a new design methodology of the gripping system suitable for the anchorage of flat strips made from fiber-reinforced polymers. The natural shape of a logarithmic spiral Nautilus shell describes the geometry of the contact surface. The continuous smoothly increasing bond stresses due to friction between the anchorage block and the CFRP strip surface enable the gripping system to avoid stress concentrations. The 3D-printed polymeric prototype mechanical tests proved the proposed frictional anchorage system efficiency and validated the developed analytical model.

Keywords: anchorage system; FRP; spiral grips; 3D printing; polymers; mechanical tests

List of Symbols

A : Constant of equation of the spiral
 E_x : Longitudinal elastic modulus of CFRP strip
 F_f : Friction force
 N : Normal force
 P : Axial force
 P_{in} : Axial force incoming the unit segment ds
 P_{out} : Axial force outgoing the unit segment ds
 ds : Length of elementary (unit) arc segment

$d\theta$: Elementary (unit) inclination angle of the tangent at ds
 f : Friction coefficient
 n : Exponent of equation of the spiral in polar coordinates
 r : Polar radius
 r_0 : Initial radius of the spiral
 r', r'' : First and second derivatives of the polar radius
 t : Thickness of flexible strip
 Φ : Golden ratio
 ε_x, u : Ultimate longitudinal strains of CFRP strip

Received: 21 December 2020; Revised: 9 February 2021; Accepted: 27 February 2021

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κ :	Curvature
ρ :	Radius of curvature
$\sigma_{x, u}$:	Ultimate longitudinal stresses in CFRP strip
φ :	Polar angle
φ_0 :	Polar angle corresponding to the initial radius r_0

1. Introduction

The stress-ribbon structural system is one of the oldest structural systems efficient for pedestrian bridges (Tubino et al., 2020) and long-span roof structures (Samih et al., 2019). The layout of the stress-ribbon structures is straightforward—a cable hanging freely between two supports describes the structural behavior; the gravity load stabilizes the deformations. However, such a structural system requires massive anchorage blocks to resist tensile stresses acting in the ribbons (Juozapaitis et al., 2021).

Several studies (e.g. Bačinskas et al., 2019; Biliszczuk & Teichgraeber, 2019; Khalifeh, 2019) identified the steel ribbon corrosion as the main drawback of the stress-ribbon systems. Besides, the relatively high weight of steel strips complicates the construction of long-span structures. Unidirectional carbon fiber-reinforced polymer (CFRP) is a promising alternative to steel because of lightweight, high strength, and excellent corrosion and fatigue resistance (Mei et al., 2015; Schlaich et al., 2015; Arnautov et al., 2016). However, the construction of the CFRP strip anchorage joints faced severe problems (Schlaich & Bleicher, 2007).

Conventional techniques, suitable for designing the strips made from anisotropic material such as steel, are not useful for CFRP components. The friction on the interface between the strip and the anchorage surface defines a typical mechanical anchorage system that induces compressive forces normal to the contact surface (De Baere et al., 2006). A cone-shaped interface between a barrel and a wedge or mechanical clamping the strip induces the compressive forces. The anisotropy of CFRP makes it vulnerable to gripping loads and local stress concentrations (Arnautov et al., 2016).

1.1. The clamping effect on mechanical properties of CFRP strips

Polymers with a unidirectional distribution of filaments are not resistant to the loads acting in directions different to the fiber orientation. For example, the 1° misalignment of the load can reduce the load-bearing capacity of unidirectional composite specimen up to 30% (Hart-Smith, 1980). The bonded end tabs developed in the late 1960s minimize the loading problems, but they can induce the specimens' premature failure because of the installing inaccuracies. The latter can alter the specimen failure manner, causing a scatter of the tension test results (Hart-Smith, 1980).

Thus, identifying basic mechanical properties requires complicated gripping systems to avoid premature shear failure of the matrix. Such damages initiate at the boundary of the specimen clamped region, leading to a brittle breakage outside the gauging length (Matsuo et al., 2019; Tahir et al., 2019). The standards ASTM D3039/D3039M and ISO 527-1 require the usage of tabs to provide a soft interface, determining static tensile properties of CFRP composites. Glass fiber-reinforced plastics (with lay-up $[0^\circ/90^\circ]_s$ or $[\pm 45^\circ]_s$) and aluminum plates are allowable for that purpose. The rigidity of tab material substantially affects the specimens' ultimate behavior (Kulakov et al., 2004; Tahir et al., 2019).

Finite element (FE) analyses of the tensile specimen with rectangular aluminum tabs show a high peak of stress tensors just behind the tabs' fixing boundary (Kulakov et al., 2004; Pagano et al., 2018; Tahir et al., 2019). The local peaks took place in the specimen upper ply close to the surface, indicating the splitting damage mode. That is a consequence of the constrained Poisson effect when the gripping device restricts the transverse deformations induced by axial tension. The low transverse resistance of unidirectional CFRP explains the premature specimen failure in the tabbed region.

Pagano et al. (2018) demonstrated that the shift of the stress peaks at a distance of 5–10 mm inward the tab boundary enables avoiding the gripped zone undesired failure. According to the Saint-Venant principle for an anisotropic medium, the deformations decay unevenly in different directions from the perturbation source. The deformation gradient is smallest in the maximum stiffness direction. Indeed, fiber-reinforced polymer materials' orthotropic nature substantially affects tabbing connection stress state, but it is not the leading cause of stress concentration. Tahir et al. (2019) observed similar effects, simulating isotropic materials though the stress peaks did not reach the results characteristic of orthotropic materials.

No standard indications on clamping pressure to avoid premature failure in the fixing zone exist. The stress concentration depends on specimen geometry (De Baere et al., 2009). The reduction of the sample thickness can reduce the unfavorable effects of the clamping pressure (Bailey & Lafferty, 2015; Alam et al., 2019; Matsuo et al., 2019; Pakdel & Mohammadi, 2019). The material, bevel angle and thickness of tabs, clamping configuration, and pressure were among the investigated variables. However, no definitive solutions supported by experimental findings have been achieved.

The axially loaded unidirectional CFRP specimen fatigue is commonly neglected. The elastic behavior of carbon fibers with almost horizontal S-N curves substantiates this hypothesis (Bunsell & Somer, 1992). However, micro-tomography scans demonstrated substantial fiber damages accumulation in clusters at high load intensity, which caused the clamping fault (Scott et al., 2012). This situation is typical for bridge operation (Schlaich & Bleicher 2007). Concerning test equipment, Hollaway (2010), Schmidt et al. (2012), Li et al. (2019), and Xu et al. (2020) pointed out the absence of reliable gripping systems economically and practically competitive with the existing anchors for tension tests of steel samples. Thus, the development of an anchorage system, preventing the failure of CFRP ribbons, is of primary interest.

This manuscript introduces a new design concept of the gripping system suitable for the anchorage of flat flexible strips made from unidirectional fiber-reinforced polymers. The natural shape of a logarithmic spiral Nautilus shell describes the geometry of the gripping system. The continuous smoothly increasing bond stresses due to friction between the fixing block and CFRP strip surface enable to form the anchorage system, avoiding undesirable stress concentrations.

1.2. Scientific rationale of the research

The ratio between the contact surface and cross-section area of flexible CFRP strips is an adequate measure for developing frictional anchors cammed with wedges or bolted plates (Portnov et al., 2006; Mohee et al., 2016; Matsuo et al., 2019). Portnov et al. (2013), Tahir et al. (2019), Ye et al. (2019), and Xu et al. (2020) demonstrated that the distribution of the shear stresses over the contact surface is not uniform in the frictional systems: The

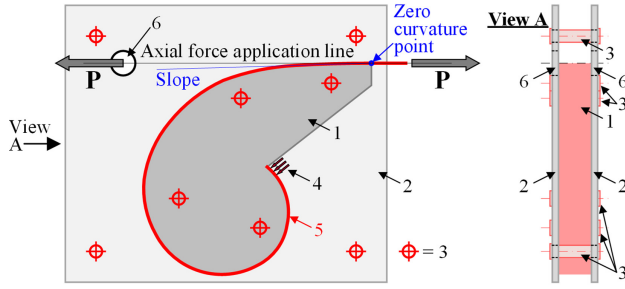


Figure 1: Schematic of the proposed spiral anchorage device of a flexible flat strip.

stress peak localizes near the entry into the gripping device. The normal stress concentration in the strip near-surface layers considerably exceeds the mean stress in the tensioned component, causing a premature failure of the polymeric strip inside the anchorage device.

The existing gripping techniques can only partially solve the above problem (Kulakov *et al.*, 2004; Burtscher, 2008; Ye *et al.*, 2019; Xu *et al.*, 2020). The frictional systems enable smooth the stress concentration, distributing those over a particular zone, but the local stresses do not disappear. The distribution shape of the shear stresses along the tensioned strip, in essence, does not change; i.e. the maximum stress appears at the entry of the gripping device and decreases inside the anchorage zone. Concerning the mechanical tests, the application of compliant interlayers in the gripping devices excluded the possibility of the device immediate reuse after the test. That highlights the need for increasing the effectiveness of the anchorage devices.

Creating a gripping system, which would help solve the above problems, provides a rationale for this work. Portnov *et al.* (2013) presented a conceptual solution that employed variable curvature grips to control shear stresses acting at the friction surface. Unfortunately, this gripping device was not capable of smoothing the shear stresses efficiently—the failure of the CFRP strip inside the gripping device resulted from the tension test. This paper proposes an alternative design concept of the gripping device, transferring tension by friction forces.

For simplicity, let us assume that gradually increased shear stresses act at one surface of the strip and transfer the applied tensile load to the spiral support because of the friction forces. The friction coefficient and curvature of the contact surface determine the distribution of the shear stresses. The contact surface curvature is equal to zero at the strip entering point and gradually increases moving inwards the gripping device. The applied load and the strip directions at the anchorage support entry (the contact point with zero curvature) coincide. The gripping device fixing point is located at the load application line to prevent the anchorage block rotation and, thereby, the frictional contact loss.

Figure 1 shows a schematic of the gripping device. In this figure, the number “1” designates the spiral support disc; “2” indicates the paired plates fixed the disc by bolts “3”; the supplemental system “4” clamps the internal end of the strip “5” before applying the tension force P ; and the hole “6” enables fixing the gripping system. Remarkably, the spiral disc “1” anchors the flat strip, transferring the applied load to the plates “2.” Thus, the tension force P induces the same magnitude reaction at the fixing point “6.”

The proposed anchorage system of a flexible flat strip enables to cumulate the shear stresses acting at the contact surface and moves the peak stress inside the gripping device. The decrease

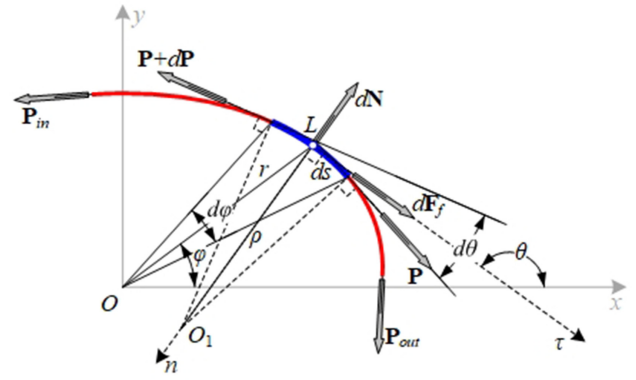


Figure 2: Schematic of load components acting on the elementary arc segment ds .

of the tension force corresponds to the cumulative action of the friction forces. The resultant tensile stresses in the strip due to the combined effect of the tension and bending loads do not exceed the CFRP tensile strength because of the balance between the curvature increase of the spiral support and the decrease of the residual tension force acting in the strip.

1.3. Analytical model of the gripping device

Let us consider the friction mechanism transferred axial force to a curved spiral surface. The simplified assumptions of constant friction coefficient, absolute rigidity of the support disc, and inextensible strip material constitute the analytical model. Figure 2 sketches the distribution of the corresponding load components. In this scheme, the point O determines the center of the planar curve; the point O_1 defines the circle of curvature drawn at a point L , which radius ρ describes the curvature radius at L . The rate of the increase of the angle $d\theta$ for the segment length ds determines the curvature at L :

$$\kappa = \frac{1}{\rho} = \frac{d\theta}{ds}. \quad (1)$$

The following equations determine the equilibrium conditions of the elementary arc segment ds in the projections on the τ and n axes (Fig. 2):

$$\tau: dP \cos \frac{ds}{2\rho} - dF_f = 0, \quad dF_f = f dN, \quad (2)$$

$$n: (2P + dP) \sin \frac{ds}{2\rho} - dN = 0, \quad (3)$$

where P , N , and F_f are the axial, tangential, and frictional forces acting on the arc segment ds , respectively. The solution of the above equation system defines the traction coefficient, i.e. the ratio between the axial load upcoming to and incoming from the arc segment (Bulín & Hajžman, 2019):

$$\chi = \frac{P_{in}}{P_{out}} = \exp \left[f \int_{\varphi_1}^{\varphi_2} \left(\frac{1}{\rho} \right) ds \right]. \quad (4)$$

The following equations determine the differential solution to the segment length ds and the radius ρ in the polar coordinate system $OL = r(\varphi)$ and the corresponding traction ratio:

$$ds = \sqrt{(dr)^2 + (r d\varphi)^2}; \quad (5)$$

$$d\varphi = \sqrt{(dr)^2 + r'^2}; \quad (6)$$

Table 1: The traction factors of some well-known curves.

No.	Spiral type	Equation	Traction ratio, P_{in}/P_{out}
1.	Fermat	$r = A\sqrt{\varphi}$	$\chi = \exp[f(\varphi + \tan^{-1}2\varphi)]$
2.	Archimedes	$r = A\varphi$	$\chi = \exp[f(\varphi + \tan^{-1}\varphi)]$
3.	Logarithmic	$r = Ae^{k\varphi}$	$\chi = \exp(f\varphi)$
4.	Hyperbolic	$r = A/\varphi$	$\chi = \exp[f(\varphi - \tan^{-1}\varphi)]$
5.	Lituus	$r = A/\sqrt{\varphi}$	$\chi = \exp[f(\varphi - \tan^{-1}2\varphi)]$
6.	Circular cylinder (Euler's formula)	$r = A$	$\chi = \exp(f\varphi)$

Table 2: The traction factors calculated for different friction coefficients ($\varphi = 2\pi$).

No.	Spiral type	Friction coefficient	Traction ratio, P_{in}/P_{out}
1.	Fermat	0.2	4.73
		0.3	10.3
		0.4	22.4
		0.5	48.8
2.	Archimedes	0.2	4.66
		0.3	10.1
		0.4	21.7
		0.5	46.9
3.	Logarithmic	0.2	3.51
		0.3	6.59
		0.4	13.0
		0.5	23.1
4.	Hyperbolic	0.2	2.65
		0.3	4.31
		0.4	7.02
		0.5	11.4
5.	Lituus	0.2	2.61
		0.3	4.21
		0.4	6.80
		0.5	11.0
6.	Circular cylinder	0.2	3.51
		0.3	6.59
		0.4	13.0
		0.5	23.1

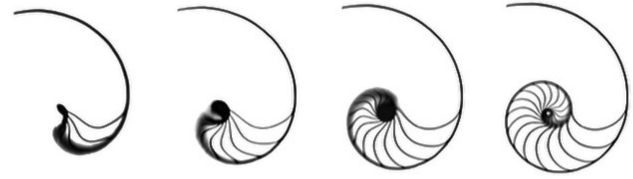
**Figure 3:** The Nautilus shell growth.

Table 1 defines the tension gradients for several well-known curves. This table demonstrates that only the logarithmic spiral has the traction coefficient χ equal to the circular cylinder. The interaction of the flexible strip with curves “1” and “2” increases the factor χ , compared to Euler’s equation (curve “6”); the contact with spirals “4” and “5” reduces the ratio χ in that regard.

Equation (8) demonstrates that the ratio between P_{in} and P_{out} acting in the branches of the flexible inextensible fragment depends on the friction coefficient f and the polar coordinates (angle φ and radius r). Thus, increasing friction at the contact surface is a promising way to raise the anchorage joint resistance. Sandpaper has a higher friction coefficient independent of the normal stresses acting on the contact area than other high-friction materials currently available in the market such as rubber gaskets and adhesive tapes. Katsumata *et al.* (2010) reported the friction coefficient (f) measurement results for different materials: 0.36 for untreated surface of CFRP laminate, 0.42 for sandblasting #100, 0.39 for sandblasting #800 of treated CFRP surfaces, 0.66 for sandpaper gasket #40, and 0.68 for sandpaper gasket #240. Table 2 lists the traction coefficients of the spirals listed in Table 1 calculated for the wrap angle $\varphi = 2\pi$ and various friction coefficients f .

Notwithstanding highest traction coefficients of the spirals “1” and “2” (Table 2), a logarithmic spiral “3” was chosen to illustrate the idea of the proposed innovative gripping system because of the simplicity of the parametric equations. The equivalence of the traction ratio of curves “3” and “6” in Table 1 also demonstrates the suitability of the cylindrical approximation (Fig. 2), i.e. the classical Euler’s formula, describing stress distribution in the flexible strip precisely.

1.4. Contributions

The nature-inspired solutions cover a wide range of engineering problems (Borges, 2004). The development of a frictional gripping device for flexible CFRP strips is the focus of this research. The Nautilus shell (Fig. 3) regulates the friction-induced shear stresses: The steady decrease of the contact surface curvature increases the contact stresses until they compensate the tensile load. The following equation describes a spiral curve in the polar

$$\rho = \frac{[r^2 + (r')^2]^{2/3}}{r^2 + 2(r')^2 - rr''}; \quad (7)$$

$$\chi = \exp \left\{ f \left[(\varphi_2 - \varphi_1) + \int_{\varphi_1}^{\varphi_2} \frac{r^2 - rr'}{r^2 + (r')^2 - rr''} ds \right] \right\}. \quad (8)$$

where r' and r'' are the first and second derivatives of the polar radius, respectively.

The following equations describe a spiral in polar coordinates, its radius, and the corresponding traction ratio:

$$r = A\varphi^n; \quad (9)$$

$$\rho = A\varphi^{|n|-1} \frac{(\varphi^2 + n^2)^{1.5}}{\varphi^2 + n^2 + n}. \quad (10)$$

$$\chi = \exp \left\{ f \left[\varphi_2 - \varphi_1 + \left| \tan^{-1} \frac{\varphi_2}{n} - \tan^{-1} \frac{\varphi_1}{n} \right| \right] \right\}. \quad (11)$$

coordinate system:

$$r = \sqrt{\Phi} \cdot \exp\left(\frac{2\varphi}{\pi} \ln \sqrt{\Phi}\right); \Phi = \frac{1+\sqrt{5}}{2}, \quad (12)$$

where Φ is the Golden Ratio (also known as the Golden Section and Divine Proportion).

As mentioned in Section 1.2, Portnov et al. (2013) made the first attempt of creating a gripping device, where the convex surface friction of grips with a variable curvature transmitted the tension load applied to the flexible CFRP strip to the anchorage device. The analytical model was developed to predict the load-bearing capacity of the frictional joint. The study demonstrated that the strip bending stress limitation defines the allowable curvature of the contact surface. These additional stresses increase with increasing flexural stiffness of the strip, which reduces the maximum possible surface curvature and increases the gripping device dimensions. However, physical tests demonstrated the developed system inability to anchorage flexible strip—the CFRP sample failure was localized inside the grips.

This study develops the frictional gripping device, diminishing peaks of shear and normal stresses on strip surface, and the concentration of longitudinal tensile stresses in the strip near-surface layers. That is the essential contribution of this work. The logarithmic spiral shape of the contact surface also makes the anchorage system compact. The gradual decrease of the contact surface curvature smooths out the friction-induced shear stresses at the contact surface. Such a system reduces the stress peaks that usually lead to premature rupture of the strip in the traditional grips. Thus, the allowable load transmitted to the strip increases by using the proposed gripping device.

The above statement, however, requires a substantiation. Mechanical tests of the 3D-printed polymeric prototype are carried out verifying the proposed gripping system efficiency. The computer-based additive manufacturing principles fit the Industry 4.0 concept that relates the revolutionary technology development to the manufacturing robots and humans interaction (Ceruti et al., 2019). The application of digital design approach, including 3D-printing technologies, also affects designers' creativeness, enabling realization of complex solutions (Zboinska, 2019). Additive manufacturing can accelerate the development process. However, 3D-printed prototypes can inadequately replicate real object mechanical behavior (Althammer et al., 2021). Thus, the structural application of printed materials requires characterization.

Extensive test program (Shkundalova et al., 2018) puts the rationale of this investigation, introducing mechanical properties of four thermoplastic polymeric materials: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high-impact polystyrene (HIPS), and polyethylene terephthalate (PETG). The brittle failure of tension specimens made from ABS, HIPS, and PETG made these plastics unsuitable for the production of printed grips; that was not the characteristic of PLA specimens, which demonstrated fundamentally different ductile failure. Therefore, this study employs the PLA material to manufacture spiral grips.

The paper organization is as follows: Section 2 describes the test program and characterization of the materials, design of the printed prototype, and testing setup; Section 3 describes the test results; and Section 4 provides the concluding remarks.

2. Test Program

This section describes several essential aspects related to the design and testing of the developed gripping system. The me-

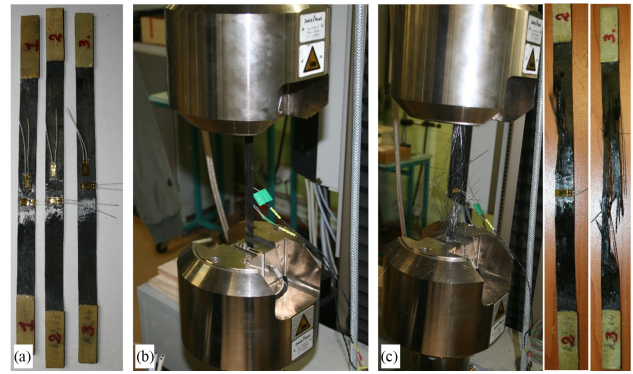


Figure 4: Tensile tests of CFRP samples: (a) specimens; (b) the specimen prepared for testing; (c) failure of the strips.

Table 3: Mechanical properties of CFRP strip.

No.	Ultimate stress ($\sigma_{x,u}$), MPa	Ultimate strain ($\varepsilon_{x,u}$), %	Elastic modulus (E_x), GPa
1.	1775.2	1.24	136.0
2.	1897.3	1.22	140.4
3.	2020.1	1.36	138.2

chanical properties of the flexible CFRP strip and the printed PLA material determine the spiral grip geometry. Therefore, Section 2.1 briefly describes the material characterization process.

2.1. Characterization of materials

The 300 mm long samples were cut from 0.5×10 mm strip made of high-strength carbon filaments and epoxy resin, using pultrusion technology. Three flat unidirectional CFRP specimens (Fig. 4a) were tested in tension according to the ASTM D 3039/D 3039M-07 standard. Figures 4b and c show the equipped sample and all specimens' failure (localized inside the gauging zone). The following mechanical parameters were obtained: ultimate stress $\sigma_{x,u} = 1897.7 \pm 49$ MPa, ultimate strain $\varepsilon_{x,u} = 1.27 \pm 0.04\%$, and elastic modulus $E_x = 138.2 \pm 0.9$ GPa. Table 3 presents the test results.

The printed material mechanical properties were determined, carrying out a tensile test of typical dumbbell-shaped samples. Shkundalova et al. (2018) reported the geometry of the specimens, printing, and testing parameters. The printed PLA tensile strength was equal to 37.7 MPa; the elastic modulus = 5.8 GPa. The spiral grips and the dumbbell-shaped samples were printed using Prusa i3 MK3 printer with identical printing parameters: extrusion nozzle temperature = 215°C; printing bed temperature = 60°C; print speed = 40 mm/s; and infill density = 60%.

2.2. The design and prototyping of the gripping system

The proposed gripping system resists the applied tension mainly by frictional forces. The friction reduces the tensile stresses, which should not exceed the CFRP local strength. A smooth change of the curvature of the contact surface controls this process. Equation (12) determines the shape of the contact surface. The initial radius r_0 defines dimensions of the gripping device. This radius depends on the flexible strip material properties (i.e. flexural stiffness and strength). The following equation

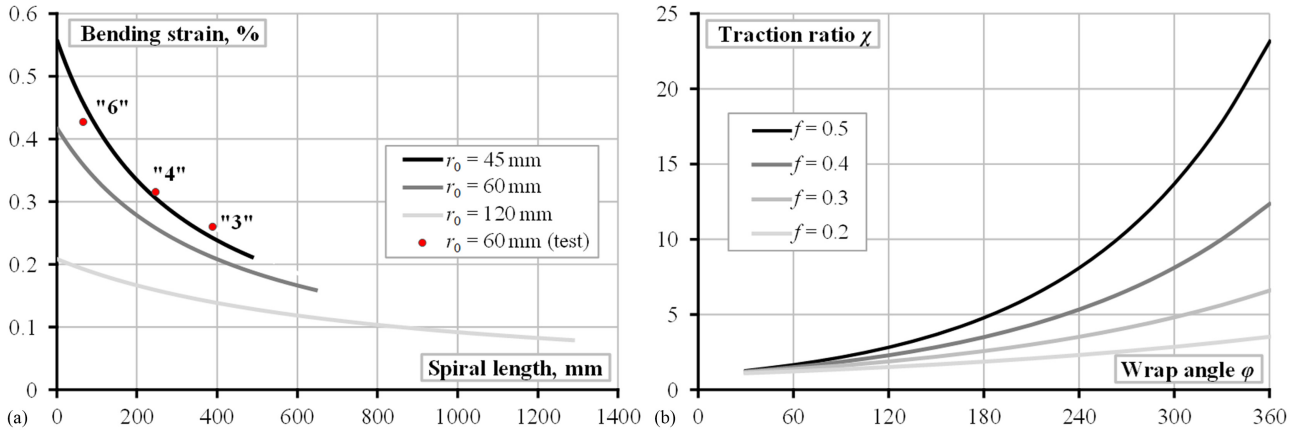


Figure 5: The behavior of the strip wrapped around the logarithmic spiral: (a) the effect of the initial radius r_0 on the bending strains of the strip (the angle $\varphi = 2\pi$ defines the contact length of the strip with the spiral surface shown by solid lines); (b) the effect of the friction coefficient on the traction ratio.

defines the angle of the initial point of the spiral (Gribniak et al., 2019):

$$\varphi_0 = \frac{\pi}{2} \cdot \left(\frac{\ln r_0}{\ln \sqrt{\Phi}} - 1 \right). \quad (13)$$

Figure 5a shows the bending strains of the flexible strip wrapped around the logarithmic spiral—the angle $\varphi = 2\pi$ and initial radius r_0 determine the strip contact length with the spiral surface. The effect of the initial radius r_0 is apparent from those diagrams. The following formula determines the bending deformations:

$$\varepsilon(\varphi) = t/2r(\varphi), \quad (14)$$

where r is the polar radius. In the considered case, the initial radius r_0 was set 60 mm to avoid stress localization in the CFRP strip due to the combined action of the tension and bending effects.

As mentioned in Section 1.3, Euler's equation (Table 1) describes the relationship between the incoming and outgoing forces (P_{in}/P_{out}), determining the ratio χ . Figure 5b shows the calculated diagram graph of the traction ratio χ for the selected initial radius (60 mm). The effect of the friction coefficient f is evident.

In this study, the actual friction coefficient was determined experimentally on a cylindrical surface, using Euler's formula (Table 1) to define the equilibrium condition of axial forces and bending moments measured during the friction test. Two situations are considered. In the first case, a friction coefficient of the polymeric disc untreated surface in contact with the CFRP strip was estimated. From five tests, it was equal to 0.20 ± 0.02 .

In the second case, sandpaper improved the contact surface friction condition by following Section 1.3 recommendations. The estimated value of the friction coefficient f of the contact between the CFRP strip and the spiral surface with glued sandpaper was equal to 0.40 ± 0.03 (average value from five tests). The corresponding diagrams shown in Fig. 5b describe the expected traction ratios.

A computer model of the spiral (12) used to print the spiral grips was developed in the Cartesian coordinate system. The following transformation relates the Cartesian coordinates and the polar coordinate system:

$$\begin{cases} x = r \cos \varphi; \\ y = r \sin \varphi. \end{cases} \quad (15)$$

Figure 6a shows a schematic of the developed layout of the spiral grips. The thick red line indicates the CFRP strip. The thin red lines sketch the Cartesian coordinates transformed using equations (15). Expression (13) has defined the angle of the initial point of the spiral curve. The scheme (Fig. 6a) was rotated to distribute the tension strip horizontally at the gripping device entrance.

The 15 mm thickness profiled parts of the gripping device were produced from the PLA material (Section 2.1) using the 3D-printing technology. However, the printed body temperature increase can cause the loss of polymeric objects' printing precision (Althammer et al., 2021). The fragmentation of the plastic body of the spiral grips (grey material in Fig. 6b) has reduced the possibility of cumulating temperature during the printing process. Three parts produced in the horizontal position composed the body of the gripping system. The printing layout of all fragments was the same: two "shells" having the 100% infill created perimeter of the printed object—the 60% printing infill distributed at rectilinear raster orientation composed the inner part of the sample. The first and last two horizontal layers of the fragments had a $\pm 45^\circ$ angle orientation and the 100% infill. Such a printing layout is typical for prototyping purposes. The printing conditions were the same as described in Section 2.1.

2.3. Mechanical tests of the gripping system

Seven $10 \times 0.5 \times 1000$ mm CFRP strip specimens from EASY COMPOSITES (UK) were used for the gripping device mechanical tests. The external tension was applied using a self-tightening wedge gripping system. The additional conical grips placed in the internal rectangular opening of the printed spiral disc (Fig. 6b) fixed the CFRP strip at the initial loading stage until the friction forces start compensating the external tension load. These grips also prevented a sudden failure of the gripping system due to the frictional contact loss; 1.5 mm thick and 45 mm length glass fiber-reinforced polymer tabs were glued on both ends of the CFRP strip specimens by a two-component polyurethane structural adhesive to protect the strip inside the mechanical grips.

The tests were carried out in three stages. At the first stage, the gripping system was tested without any additional treatment of the surface being in contact with CFRP strip. The second and third testing stages considered the grips with the improved contact surface friction performance, using sandpaper (Section 2.2). At the first two testing stages, both internal and

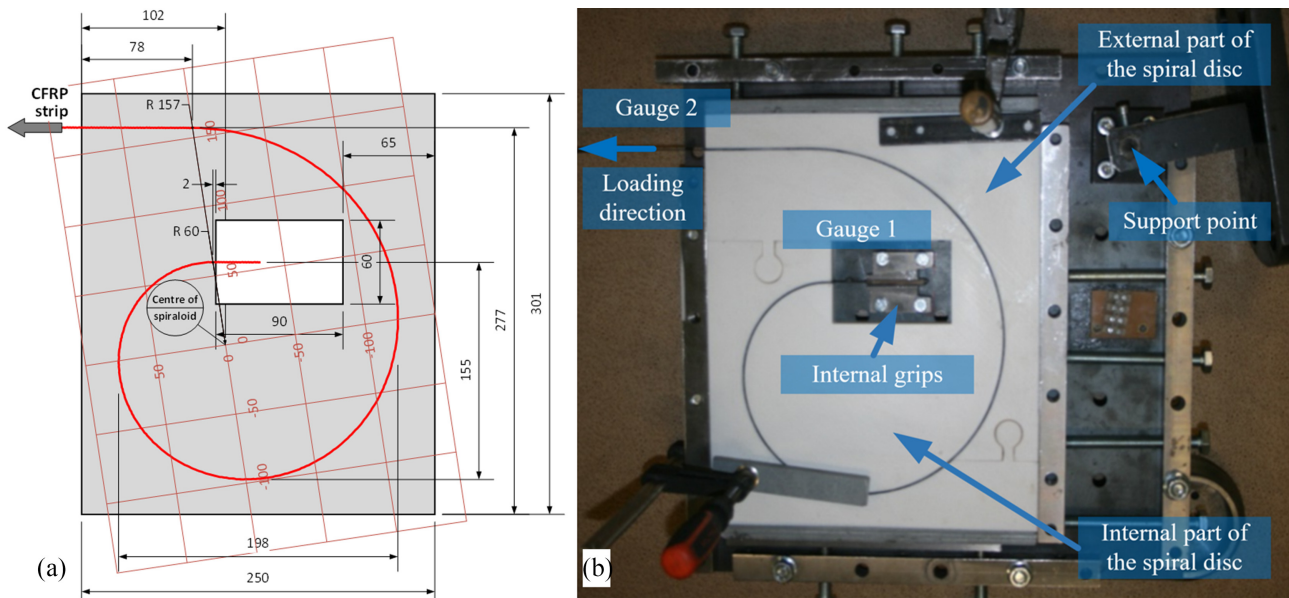


Figure 6: Layout of the spiral gripping system (Gribniak et al., 2019): (a) a scheme (dimensions are in mm); (b) loading apparatus.

Table 4: Test results of the spiral gripping system prototypes.

No.	Friction coefficient (<i>f</i>)	Failure type	Ultimate stress ($\sigma_{x,u}$), MPa	Ultimate strain ($\epsilon_{x,u}$), %	Elastic modulus (E_x), GPa
1.	0.2	I	1000	0.73	155.0
2.	0.2	I	1500	0.61	148.6
3.	0.2	II	1412	–	155.6
4.	0.4	III	1932.5	1.38	149.8
5.	0.4	III	1897.3	1.25	138.3
6.	0.4	III	1849.6	1.14	144.3
7.	0.4	III	1756.0	1.10	133.7

external parts of the polymeric grips fixed the CFRP strip (Fig. 6b). At the third testing stage, the CFRP strip was wrapped around the spiral disc internal part without confinement by the polymeric disc outer part. The sandpaper was renewed after every test of the gripping system. The mechanical grips fastened both the CFRP strip ends after placing the strip in the gripping device. A circuit plate with the gripping device was placed in a servo-hydraulic testing machine MTS 809.40 in a central position. The machine crosshead speed was 3 mm/min and prevented jerks at the initial loading stage. During the test, the applied load and strip strains were recorded.

At the first two testing stages, the adjustment screws were tightened with a 9 Nm torque to confine the spiral grips inside of the steel frame. Two strain gauges with a base of 1.5 mm and a resistance of 120 Ω monitored the deformations of the CFRP strip: One was placed in the gap between the inner edge of the spiral surface and the internal grips, and another device was attached outside the spiral disc (close to the polymeric surface).

Table 4 summarizes the results. In this table, the failure type “I” defines the strip pulled out the grips; “II” corresponds to the strip failure inside the gripping system; and “III” designates the strip failure outside the polymeric grips. The first testing stage results demonstrate that the untreated grips ($f = 0.2$) could not anchor the CFRP strip. An increase in the friction coefficient to 0.4 by using sandpaper at the second testing stage ensured a

sufficient resistance of the polymeric grips for achieving the maximum load-bearing capacity of the anchorage system (Table 4). Thus, the further analysis focuses on the mechanical behavior of the frictional grips with $f = 0.4$.

Figure 7a shows the CFRP strip strains related to the applied load (sample 5, Table 4). The diagram demonstrates substantial differences between the deformations monitored inside (Gauge 1) and outside the spiral grips (Gauge 2). This difference results from the friction between the contact surfaces of polymeric grips and the CFRP strip, though the steel frame confinement increased the friction effect. Figure 7b shows the ratio between the readings of the Gauges 2 and 1. Figure 7c demonstrates the failure of the CFRP strip localized outside the grips. The ultimate tensile stress and strain in the tested strip gauged section (the average values from specimens 4–6, Table 4) were 1893.1 ± 21.0 MPa and $1.25 \pm 0.04\%$, respectively, and the elastic modulus = 144.3 ± 3.0 GPa. These values well agree to the tensile test parameters determined in Section 2.1.

At the third testing stage, the CFRP strip was wrapped around the grip inner part without external confinement, as shown in Fig. 8a. The assemblage and loading conditions remained the same as in the first two testing stages except for the steel frame deformation confinement. However, the confinement condition differences did not alter the CFRP strip failure mechanism—the breakage was localized outside the polymeric grips (i.e. failure type “III,” Table 4).

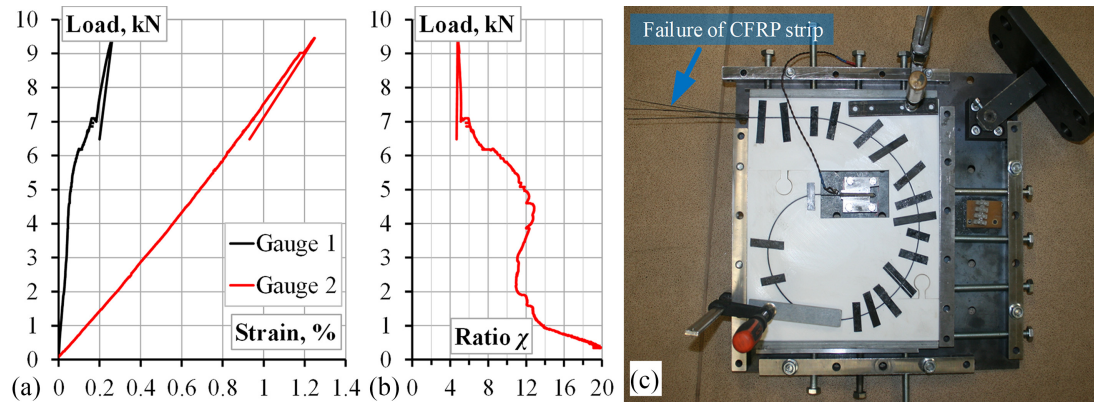


Figure 7: The test results of the printed grips: (a) load-strain diagrams of internal (Gauge 1) and external (Gauge 2) indicators; (b) the corresponding traction ratio; (c) failure of the CFRP strip (failure type “III,” Table 4).

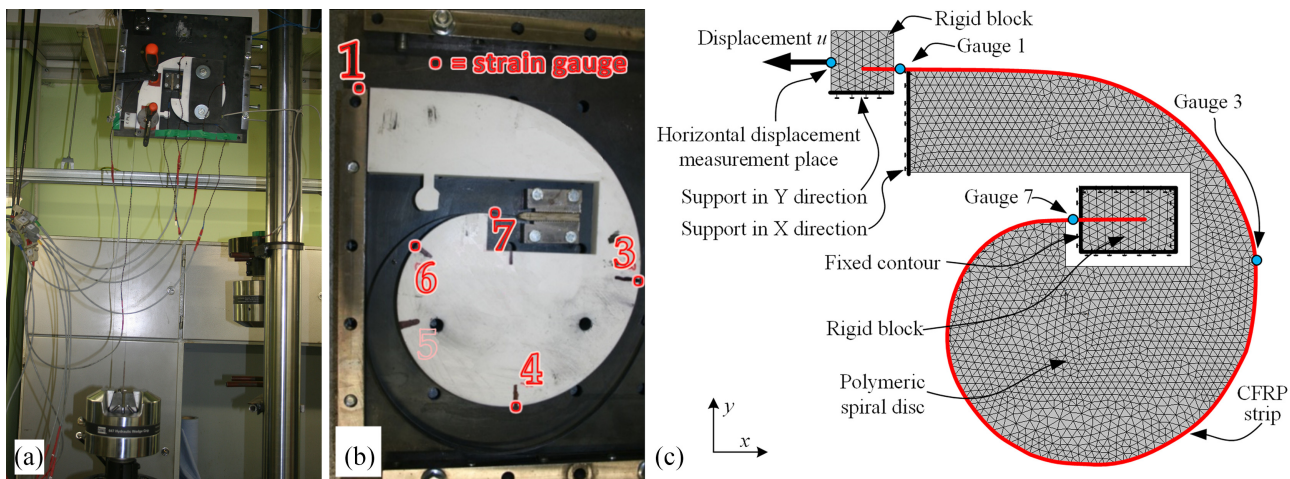


Figure 8: Mechanical test of the internal part of spiral grips: (a) test setup; (b) spiral disc with indicated numbers of the strain gauges (the numbers “1” and “7” correspond to the external and internal indicators); (c) FE model of the disc.

Five additional strain gauges were fixed to the outer part of the strip over the contact surface. Figure 8b shows the strain gauge distribution scheme. At fully assembled spiral anchor (before the mechanical tests), the bending deformations of the strip measured by strain gauges were $\varepsilon_3 = 0.265\%$, $\varepsilon_4 = 0.315\%$, and $\varepsilon_6 = 0.427\%$. The readings of Gauge 5 were lost due to the failure of the measurement device.

3. Discussion of the Test Results

Figure 7b demonstrates that the average traction ratio χ is equal to 12.2 until the 6 kN load. That agrees to the calculated value of 13.0 (Table 2)—the prediction difference is equal to 6.7%. The coefficient χ decreases approximately to five, increasing the load. The epoxy resin, blunting of the sandpaper, reduces the coefficient of friction through the contact length. That contradicts to the constant friction assumption of the theoretical model. High deformability of the polymeric material (the elastic modulus of the printed PLA = 5.8 GPa, Section 2.1) also contradicts the analytical model (Section 1.3) and could cause the observed disagreement. Even small changes in the original spiral surface shape can lead to considerable changes in the CFRP tensile stresses.

An FE model (Fig. 8c) was developed to illustrate the above effect. The model was verified using the third testing stage results (when the CFRP strip was wrapped around the spiral disc inner part without external confinement, Fig. 8a). Figure 9a shows the diagrams obtained, using the strain gauges' readings related to the external tension load (P). Figure 8b shows the strain gauge distribution scheme—the indicators “3,” “4,” and “6” measured deformations of the strip above the contact surface with the spiral support. The strain gauges “1” and “7” were glued to the CFRP strip at the frictional gripping system entrance and exit. The latter two indicators determined diagrams similar to the graphs identified at the second testing stage (Fig. 7a). The steel frame confinement effect could explain the disagreement between the ultimate strains $\varepsilon_{x, u}$ shown in Figs 7a and 9a.

Remarkably, Fig. 9a shows the deformation diagrams ignoring the bending effects, i.e. the readings by the gauges “3,” “4,” and “6” were zeroed before the tension test. Figure 9b shows the total deformation diagrams, including the bending strains measured after placing the flexible strip on the spiral disc (before the mechanical tests). The deformation onset of the graphs “3,” “4,” and “6” was 0.265%, 0.315%, and 0.427% (Section 2.3). Figure 5a compares these onset values to theoretical predictions (Section 1.3). The prediction adequacy proves the analytical model correctness.

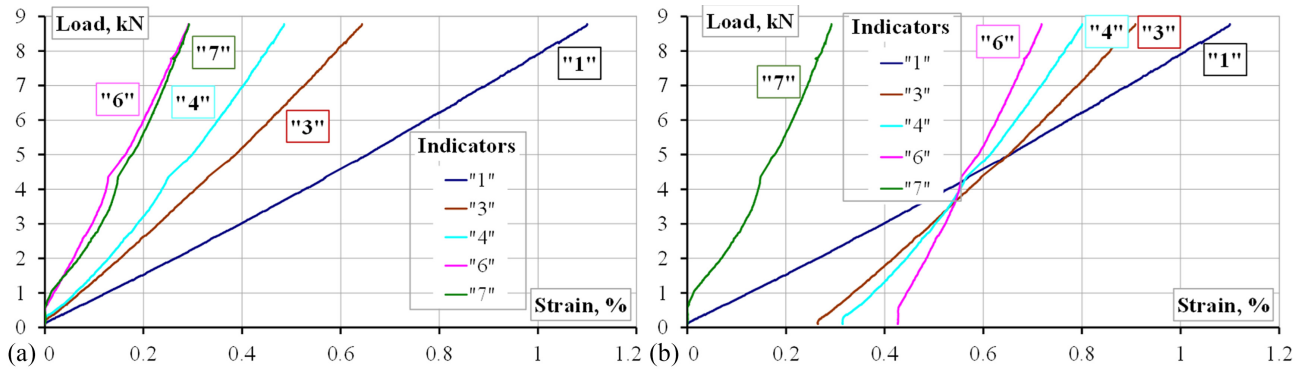


Figure 9: Deformation measurement results of CFRP strip (Fig. 8b describes numbering of the strain gauges): (a) test results; (b) transformation accounting the bending effect.

The slope of the diagrams “3,” “4,” and “6” is dependent on the distance of strain gauges to the strip entrance to the gripping device. This deformation behavior is associated with the friction force cumulative nature, reducing deformations of the strip—the decrease in the strains decreases the curve slope. Noticeably, none of the modified diagrams (Fig. 9b) reaches the CFRP strip ultimate deformations observed during the tension tests (Table 3). On the one hand, that proves the correctness of the choice of the initial radius r_0 (Section 2.2). The consistency of the mechanical parameters of CFRP strips presented in Tables 3 and 4 (elements 4–6) proves the proposed frictional grips for the testing purpose.

On the other hand, the lack of the steel frame confinement can cause the differences between the test results of the elements 4–6 and sample 7 (Table 4). Still, the linearity of the diagrams shown in Fig. 9 establishes the absence of sudden changes in the CFRP strip contact conditions, revealing the reliability of the proposed gripping concept.

A non-linear FE analysis was carried out to illustrate the spiral disc rigidity effect on the strain distribution in the CFRP strip. The commercial FE software ATENA was used for that purpose. Figure 8c shows the FE model. The deformation problem was solved in a two-dimensional formulation; the spiral disc was meshed using triangular shape FEs, having 5 mm average size. The external cable elements (Cervenka et al., 2020), i.e. the truss elements fixed at the contact points and freely sliding over the polymeric disc between the supports, simulated the CFRP strip. A section of the cable between the fixing points was considered a uniaxial bar element; the same law of dry friction (with

coefficient $f = 0.4$) governed all contact points’ movements and the strip strain distribution. This modeling approach does not require introducing the interface elements, simplifying the solution to the contact problem.

Two FE models were built in this study. The CFRP strip was modeled, assuming a bilinear stress-strain material law in both cases. The first simulation took an elastic isotropic material model of the polymeric disc; the experimentally determined mechanical parameters (Section 2.1) described the printed material model. The alternative FE model employed a rigid material of the spiral disc to investigate the stiffness effect on the anchorage joint deformation behavior.

The boundary conditions of the models were defined by the physical test described in Section 2.3. The horizontal displacement was applied to a rigid block with a fixed CFRP strip in 0.1 mm increments until the material strength exceeded. The principal strains of the CFRP strip were monitored in several locations. Figure 8c shows the boundary and loading conditions, and strain monitoring points, which correspond to the strain gauge positions shown in Fig. 8b.

Figure 10a shows the experimental strain distribution in the CFRP strip and predictions by the “elastic” disc model. The solid lines describe the test measurements; the dashed lines show the numerical predictions. The numbers on this figure represent the strain gauge positions (Fig. 8b). The consistency of the predicted and experimental results proves the adequacy of the FE model. Overestimation of the indicator “1” outcomes can result from local movements of the unconfined internal part of the support

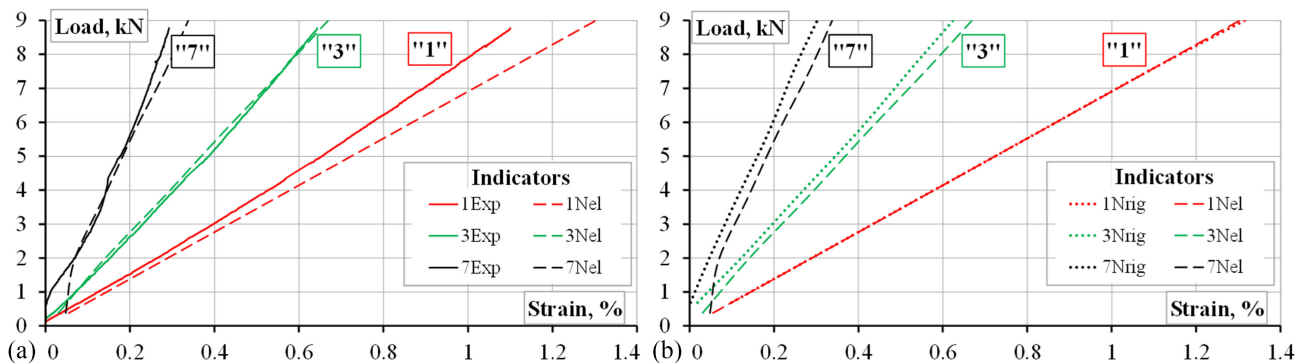


Figure 10: FE predictions of deformation behavior of CFRP strip (Fig. 8b defines the strain gauge numbers): (a) comparison of the elastic disc model with the test results; (b) juxtaposition of the rigid and elastic disc models.

disc inside the steel frame (Fig. 8a), which were ignored in the numerical simulation.

Figure 10b shows the deformation prediction results by the alternative FE models. The dashed lines represent the same predictions, as shown in Fig. 10a; the dotted lines define the “rigid” disc model results. The support stiffness effect is apparent—the traction ratio χ increases with increasing the grips stiffness. The relative difference between the models’ predictions, expressed in terms of the ratio χ , decreases with the load that agrees to the tendency shown in Fig. 7b. The frictional contact loss caused a further decrease in the coefficient χ observed during the mechanical tests, which was ignored in the numerical simulations.

4. Concluding Remarks

This manuscript introduces a new design methodology of the gripping system suitable for the anchorage of flat flexible strips made from unidirectional fiber-reinforced polymers. The nature-inspired choice of the logarithmic spiral shape of the contact surface makes the anchorage system compact. The analytical model suitable for the design of the spiral grips was also proposed. The mechanical tests of the 3D-printed polymeric prototype proved the efficiency of the proposed gripping system and validated the developed analytical model.

The tested prototype shows the working example of the efficient gripping system. The frictional anchorage system having the initial radius of 60 mm and the friction length corresponding to the rotation angle 2π has reduced the tension stresses approximately 10 times. The failure of the CFRP strip was localized outside the gripping system. No signs of the sudden changes in the CFRP strip contact conditions were observed in the experiments. That reveals the reliability of the proposed gripping concept.

The test results demonstrate the necessity of modifying the proposed theoretical model accounting for the component deformations. The simplified friction theory based on Euler’s and Amonton’s laws could also be inadequate to predict the frictional system ultimate behavior. That is the object of further investigations.

Acknowledgment

The authors acknowledge financial support received from European Regional Development Fund (Project No. 01.2.2-LMT-K-718-03-0010) under grant agreement with the Research Council of Lithuania (LMTLT).

Conflict of interest statement

None declared.

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